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VISUAL REPAIR OF CONGENITAL AORTIC STENOSIS DURING HYPOTHERMIA

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CONGENITAL obstruction to left ventricular outflow, either at the aortic valve or at subvalvular level was formerly considered to be both relatively uncommon and benign. Abbott,[1] in reporting 1,000 cases of congenital heart disease, found 18 instances of subvalvular and 11 of valvular aortic stenosis. Nadas[2] stated that these 2 lesions accounted for slightly over one per cent of his patients with congenital heart disease. Campbell and Kauntz,[3] however, reported 40 patients and emphasized that the lesion is more common than is generally thought. The 11 surgical patients in our present series were selected from a total of 57 patients with congenital valvular or subvalvular stenosis. These 57 patients represent about 5 per cent of the total individuals observed in our clinic with congenital heart disease during the past 6 years. Certainly the incidence is far below that of septal defects but, nontheless, obstruction to left ventricular outflow is not a rare lesion.

The benignity of this disease has also been subject to some question in recent years. In a group of 37 patients, Downing[4] reported three instances of sudden death. Nadas[2] encountered 5 such accidents in a group of 67 patients and, more recently, Braverman and Gibson[5] reported comparable figures with 6 cases of sudden death in a series of 73 patients followed over an 8-year period, an incidence of 8.2 per cent. We have had 3 cases of sudden death in our group of 57 patients, or 5.2 per cent. It is apparent, therefore, that the lesion is far from benign and a safe and effective operative procedure would have much to recommend it.

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The first operative attacks on congenital obstruction were transventricular, using instrumentation similar to that employed for rheumatic aortic valvular stenosis. Bailey[6] stated that the small aortic lumen in children makes this approach technically easier than the closed transaortic route, since the vessel is too small to accommodate the finger. Marquis and Logan[7] reported 6 patients operated upon via the ventricle. All but one patient had postoperative aortic insufficiency which was considered to be severe in 2, moderate in 2, and slight in one. Downing[4] reported 19 operative patients with one operative death and one death due to a cerebral vascular accident several months postoperatively.

Experimentally, open operation on the aortic valve, using circulatory occlusion, was first described by Carrel[8] in 1914. Apparently little further study of the problems involved were undertaken until the work of Clowes and Neville[9] in 1954. In accord with our often expressed opinion that most, if not all, intracardiac operations can better and more safely be done under direct vision, an experimental technique for the transaortic exposure of the valve during circulatory arrest and hypothermia was evolved in our laboratory in early 1955. Emphasis was placed on methods to prevent trapping of air in the heart to avoid coronary air embolism. The first patient to have a successful direct vision procedure on the aortic valve was operated upon Nov. 17, 1955. The experimental technique and the course of the patient have been previously reported.[10] Very shortly thereafter, Lewis and his associates,[11] also using circulatory occlusion during hypothermia, successfully operated upon a patient with congenital aortic stenosis by the transarterial open approach. Kay and Morrow[12] employed this method in a patient with subaortic stenosis.

A different method for the open transaortic approach to the aortic valve has also recently been developed and applied clinically. That the heart might be nourished by retrograde venous perfusion was first suggested by Pratt[13] in 1898, and subsequently demonstrated by Roberts, Browne, and Roberts[14] in 1943. Experimentally, Blanco, Adam, and Fernandez[15] developed a method for general body perfusion combined with retrograde perfusion of the coronary sinus which allowed exposure of the aortic valve. Based on these studies, Lillehei and co-workers[16] have applied the method clinically. This technique has the advantage of providing a somewhat longer safe period for the open procedure, but has the disadvantage that the operative field instead of being dry is constantly flooded by coronary blood flow.

The 11 patients presented here were all operated upon using general hypothermia, circulatory arrest, and open, transaortic plastic revision of their stenotic lesion.

PATHOLOGY

Three of the 11 patients had subvalvular obstruction while 8 had valvular stenosis.

Subvalvular stenosis in all 3 patients consisted of a ring or collar of firm, whitish, fibrous tissue encircling the outflow tract of the left ventricle. This ring was located from 1.0 to 2.0 cm. below the valve in each instance. The ring involved the lowest edge of the right valve cusp in one patient (Fig. 1). The

Fig. 1.

Fig. 2.

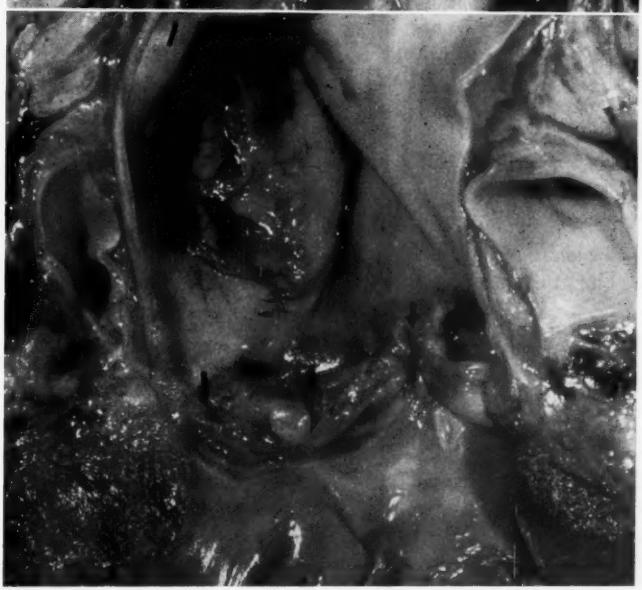

Fig. 1.—The autopsy specimen from a patient with subvalvular stenosis who died of tracheobronchitis 5 days after operation. The remaining portion of the fibrous constricting collar is seen to lie just below the cusps of the aortic valve. The dotted line indicates the extent of the resection at the time of surgery.

Fig. 2.—The autopsy specimen from a patient who died on the twenty-seventh day following operation of hemorrhage from the aortic wound. The arrows indicate the sites of incision. The two lateral ones were properly placed in the commissures, but the central one created moderate insufficiency since the commissure (not seen behind the cusp) did not extend completely up to the lip of the cusp.

posteromedical attachment of these obstructing collars was across the ventricular aspect of the aortic leaflet of the mitral valve. This is a relationship of extreme importance as well be discussed later. There was no definable infundibular chamber observable in the left outflow tract distal to the obstruction. Of great importance, however, was the uniform participation of the valve and the valve ring in the phenomenon of post-stenotic dilatation. This dilatation was already established in the intramyocardial aorta so that the diameter of the valve ring was considerably greater than normal. The sinuses of Valsalva were also grossly enlarged and the valve cusps were moderately thickened. This participation of the valve and the most proximal portion of the aorta in the post-stenotic dilatation may contribute a radiographic contour suggesting the subvalvular location of the lesion and also permits operative exposure through the valve ring via the aortic incision. In one patient, a small patent ductus arteriosus was present in association with subvalvular stenosis.

Valvular stenosis was similar, in general, to the Type II stenosis of the pulmonary valve which we have previously described.[17] The cusps were formed, and thickened fused commissures existed. The opening in the valve in all patients was remarkably constant, averaging about 8 mm. in diameter. The commissures were at times irregularly fused so that the valve orifice lay somewhat eccentric. The cusps, and most particularly the free edge of the cusps, were thickened and firm. However, in no patient was calcification present. We did not encounter a valve similar to the Type I pathology in which only rudimentary commissures were present and the valve was an inverted funnel. This, however, has been described.[18]

Bicuspid valves were found in 2 of the 8 patients with valvular stenosis, and another had essentially a biscuspid valve except that the third commissure was partially formed. In the truly bicuspid valve, the orifice was a slit-like structure, and the surgeon had the impression at operation that incision of the commissures had minimal effect upon the capacity of the thickened valve cusps to open more widely. The incompletely formed commissure in the third patient with a bicuspid valve came to within 2 mm. of the free edge of the cusp and thus created the illusion of a tricuspid valve (Fig. 2). Incision of this incompletely formed commissure resulted in significant postoperative regurgitation. It is extremely important, therefore, that the operator realize the possibility of incomplete formation of commissures and avoid incision into such commissures if they are present.

The post-stenotic dilatation beyond valvular stenosis began just distal to the uppermost attachment of the commissures to the wall of the aorta. The vessel was dilated to approximately twice its normal size in the ascending portion and then gradually tapered to normal in the first portion of the arch. This dilatation is not associated with hypertrophy of the aortic wall. Indeed, the vessel in this area is thinner and more friable than in the descending aorta. Thus, the dilatation enhances the ease of application of tangential noncrushing clamps; the narrow segment just above the valve renders exposure of the valve more difficult; and the friable nature of the aortic wall makes closure of the incision both difficult and dangerous.

CLINICAL CONSIDERATIONS

The relative frequency of subvalvular as compared with valvular stenosis has been difficult to ascertain in the past. Certainly the only conclusive answer heretofore depended upon necropsy findings, as even an operative approach through the left ventricle would not decide this question. The clinical literature relative to this subject, therefore, has led to considerable confusion. Thus, some years ago, when it was popular to consider the obstruction as usually subvalvular in origin, reports by Young[19] and Brofman and Feil[20] described the classical picture of aortic obstruction and considered it to be due to subaortic stenosis. It would seem probable, at the present time, that the majority of these patients had the obstruction at the valvular level. More recently, the identical clinical picture has been considered to reflect aortic valvular stenosis.[3, 4, 21]

There has also been considerable confusion as to the etiology of aortic valvular obstruction. Some of the patients presented as having congenital aortic valvular stenosis by Campbell and Kauntz[3] might be considered to be of rheumatic or dengenerative origin by other observers. However, since it is apparently true that a patient with relatively mild aortic valvular stenosis may develop degenerative changes and thus present, in later years, with calcific aortic stenosis, it is difficult if not impossible at this stage to determine the exact etiology from clinical evaluation. It is evident that in order to be certain that the valvular stenosis is congenital in origin, one would have had to evaluate personally the case prior to the tenth year of life and to have found the classical clinical picture of aortic obstruction without any history of rheumatic disease. Even the history of a murmur from childhood in a patient 40 years of age is not adequate background upon which to make a diagnosis of a congenital deformity, as the murmur might have had a different origin.

The patients in the present series were all below 15 years of age, with but one exception, and a murmur associated with the classical clinical picture was noted prior to the age of 12 in all but 2 patients. The actual pathology was also observed in a dry field at the time of surgery in all patients. Therefore, in this present series, no doubt exists as to the congenital etiology of the lesion, nor as to the site of the obstruction.

Symptomatology.—Reliance on symptoms in evaluating the severity of obstruction in children with congenital aortic stenosis is not rewarding and, actually, may be most misleading. Relatively severe obstruction may exist without any symptoms whatsoever. The presence of dizzy spells and bouts of syncope are ominous symptoms and may presage sudden death. On the other hand, sudden death may occur without any previous symptom. The finding of decreased exercise tolerance is at times noted, but this is frequently difficult to assess in a child. The development of congestive failure is uncommon, but does occur. Thus, in general, the problem is similar to evaluating patients with pulmonary valvular stenosis and an intact ventricular septum, in whom symptoms are also misleading. In both instances, the patients may have severe obstruction and yet have minimal symptomatology. In the over-all clinical evaluation of the

patient, therefore, the physical findings, electrocardiogram, and fluoroscopic examination are the important factors in the evaluation of the severity of the obstruction.

Physical Findings.—The classical physical findings have been well outlined by previous authors.[2, 3, 22, 23] The body habitus is usually normal. A systolic thrill to the right of the upper sternum and transmitted into the neck vessels is almost always present, as it was in all patients in our group. The thrill may be rather diffuse over the precordium, but is usually maximum to the right of the upper sternum. Palpation of the apical area of the precordium will frequently reveal a forceful sustained thrust that is associated with left ventricular hypertrophy. The peripheral pulse may be entirely normal or may be small, and the blood pressure and pulse pressure may be normal, or there may be a somewhat lowered systolic pressure and a decreased pulse pressure. These findings vary, in general, with the severity of the aortic obstruction.

Auscultation reveals a loud harsh systolic murmur, well heard at the base, and usually of maximum intensity in the first or second right intercostal spaces at the sternal border and well transmitted into the neck vessels. In the patients with subaortic stenosis, we believe that the murmur is frequently of maximum intensity somewhat lower in the third intercostal space and beneath or just to the left of the sternum. This was true in the 3 patients with subaortic stenosis in this series. A diastolic murmur of aortic insufficiency was not present in any patient in this group.

In distinguishing subvalvular from valvular stenosis, the intensity of the second aortic sound has not proved to be of any value. In congenital valvular stenosis, the second aortic sound is usually of entirely normal intensity and may at times be increased. The reasons for the latter finding are certainly not clear.

Electrocardiography.—The electrocardiogram offers valuable information in determining the severity of the obstruction. Evidence of left ventricular hypertrophy is considered to be a most reliable sign of the severity of the aortic obstruction. The electrocardiogram, however, may be within normal limits even in the presence of definite hypertrophy of the left ventricle, since it is not a very sensitive reflection of the degree of left ventricular hypertrophy. Therefore, the definite presence of left ventricular hypertrophy in the electrocardiogram implies significant stenosis, and the earlier in life that this is present, the more significant is the finding. In addition, to the changes in the QRS complexes, reflecting left ventricular hypertrophy, the T waves are usually inverted in the left precordial leads. Thus, the changes are suggestive of the so-called "systolic overload pattern," as described by Cabrera.[24] The electrocardiogram is particularly valuable, therefore, in the patient with no symptoms and a heart that is within normal limits as regards over-all size. Severe stenosis and hypertrophy of the left ventricle may be present, reflected only by the electrocardiogram.

X-ray and Fluoroscopy.—The main pulmonary artery and its branches were considered to be normal in size and amplitude of pulsations in all patients. Dilatation of the ascending aorta has been mentioned by most observers as being a prominent feature of the fluoroscopic evaluation of patients with aortic obstruction.[2, 4, 5, 22] It is considered that the site of the post-stenotic dilatation may be of some aid in differentiating subvalvular from valvular obstruction. At surgery, we have noted that in subvalvular stenosis, the most proximal portion of the aorta including the sinuses of Valsalva take part in the post-stenotic dilatation; whereas, in valvular stenosis, the post-stenotic dilatation is noted to take its origin distal to the sinuses of Valsalva. Therefore, at the time of fluoroscopy, this was looked for very carefully. However, this is very difficult to evaluate with any degree of accuracy, since the very proximal dilatation lies within the shadow of the heart. However, in the 26-year-old patient with subaortic stenosis, the low dilatation was clearly noted on fluoroscopy and appeared as a double contour within the cephalic portion of the right atrial shadow. The patients with valvular aortic stenosis revealed a tendency for the post-stenotic dilatation to begin farther along in the ascending aorta.

The heart was within normal limits or very slightly enlarged as regards over-all size, but the configuration was abnormal. In all of our patients, the configuration of the left ventricular salient was suggestive of hypertrophy of the left ventricle. The left atrium appeared to be slightly enlarged in some patients, but this was not a consistent finding. No enlargement of the right atrium or right ventricle was observed and, although looked for carefully, there was no evidence of calcification in the area of the aortic valve in any of these patients.

Ancillary Investigations.—Ancillary measures have been resorted to but infrequently in the present group of patients and, in general, we have not considered that they offer anything in the establishment of the diagnosis. Direct pressure tracings from a peripheral artery or from the aorta always revealed changes reflecting the obstruction to outflow from the left ventricle into the aorta. In patients with less severe stenosis, this tracing may be normal. Brofman and Feil[20] considered evaluation of the recorded arterial pulse tracing as helpful in the differential diagnosis between valvular and subaortic stenosis. However, most other observers do not agree,[5, 22, 25] and it has been our experience that peripheral artery pulse curves are of no value in making this differential. Thus, while the peripheral arterial tracing reveals findings reflecting the stenosis, it is not a sensitive indication of the severity of the stenosis and in no way differentiates subvalvular from valvular stenosis.

Right heart cardiac catheterization is not considered to be of any value in the diagnosis of aortic obstruction. The cardiac output and pressures within the right heart are within normal limits in most instances. Downing,[4] however, has reported the finding of pulmonary hypertension in several instances. The left atrial pressure is frequently elevated in severe aortic obstruction. Retrograde transmission of the elevated left atrial pressure across the capillary bed might elevate the pulmonary artery pressure; or it is conceivable that, in certain

susceptible individuals, the elevated pulmonary venous pressure might give rise to reflex mechanisms that would further elevate the pulmonary artery resistance and pressure.

Left heart catheterization would, of course, offer the most valuable information. The simultaneous recording of pressure within the left ventricle and aorta and the determination of the gradient across the aortic obstruction, when considered with the cardiac output at that time, would reveal rather accurately the severity of the obstruction. However, most of our patients have been children, the left atrium has been of normal size or but slightly enlarged, and it has not been considered advisable to perform left heart catheterization in these patients. Thus, while this would be valuable information to obtain pre- and postoperatively, we have not considered that left heart catheterization is such a benign procedure as to warrant its use in these patients.

SURGICAL CONSIDERATIONS

The avoidance of coronary air embolism, critical to the success of open transaortic approach to the aortic valve, depends first on the fact that exposure of the coronary ostia to air with a beating heart does not tend to drive air into the coronary arteries and, second, upon the development of effective methods to displace all air from the heart and aorta at the time of retreat from the heart. Our experience in this group of patients concerning the first factor has amply confirmed the experimental observations previously reported.[10] There is no tendency for air to enter the coronary system when the valve is exposed to atmospheric pressure.

As regards the second factor, many of the elaborate precautions taken in the earlier patients have not seemed necessary as experience has increased, so that the technique has been modified in the interest of simplification. Dissection, mobilization, and clamping of the lung roots, the right coronary artery, and the great vessels of the arch of the aorta have all been omitted as not apparently essential in the prevention of air embolism. Only one patient in this series had air enter the right coronary arteries and this was easily managed by finger massage and temporary cross-clamping of the aorta.

The current technique, therefore, is briefly described as follows. The patient is rendered hypothermic by surface immersion[26] and the lowest rectal temperature sought is 30° C. The transverse bilateral sternal-splitting incision is in the third interspace. The patient is positioned with the head of the table elevated and turned 20 degrees toward the right side. The venae cavae are mobilized and tapes placed around them. The aorta is carefully dissected downward at its base, mobilizing the fat pad in the groove between aorta and right ventricle and auricle until the myocardial portion of the aorta is reached. The right coronary artery is carefully observed and protected A flap of pericardium and adventitia, hinged laterally, is now raised over the proposed site of incision in the aorta, which should be in the most proximal portion of the aorta possible. Four stay sutures of 5-0 arterial silk are now appropriately placed in the aorta and a specially designed noncrushing clamp is applied (Fig. 3). This maneuver

may be facilitated by temporarily occluding the venae cavae so that arterial blood pressure is momentarily lowered during the careful application of the clamp. The bite should be big enough to provide adequate tissue for incision, but not so great as to occlude blood flow in the aorta or obstruct the lumen of the ostium of the right coronary artery. The incision in aorta is made about 3 or 4 cm. in length.

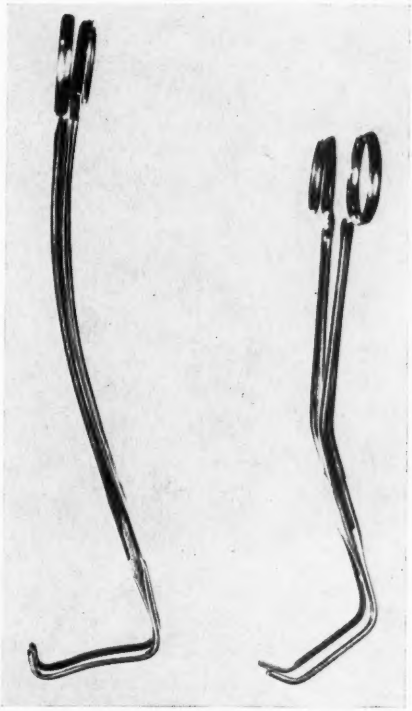

Fig. 3.—Specially designed noncrushing clamps which have proved valuable for the aortic incision just above the valve. The clamp on the left is made by George P. Pilling and Son, Philadelphia, Pa., the one on the right by Bruno Richter, Lombard, Ill.

Inflow occlusion of the heart is now effected by traction on the caval tapes. A clamp is placed across aorta and 1.0 to 1.5 ml. of 1:4000 Prostigmin is injected proximally for coronary perfusion to slow the heart and protect against ventricular fibrillation. The transaortic clamp is removed. A noncrushing clamp is now placed across main pulmonary artery. The transaortic clamp is replaced after a few beats of the heart, and the clamp on the aortic incision is now removed. The aorta is usually entered about one minute after inflow occlusion has been achieved. After some blood loss as the heart empties the pulmonary veins, left auricle and ventricle, the field becomes completely dry.

The principle of the operation is based on the supposition that the thickened fused commissures can be accurately incised toward their insertion on the aorta

in such a fashion that the cusps on both sides retain part of the commissural tissue and thus remain intact and competent. If no commissures are present, this principle could not be applied, without creating disastrous regurgitation. In this series of patients, as much incision as deemed possible was made in all three commissures (or in both commissures of a bicuspid valve). The operation on the valve itself, therefore, was maximal in terms of the underlying principle.

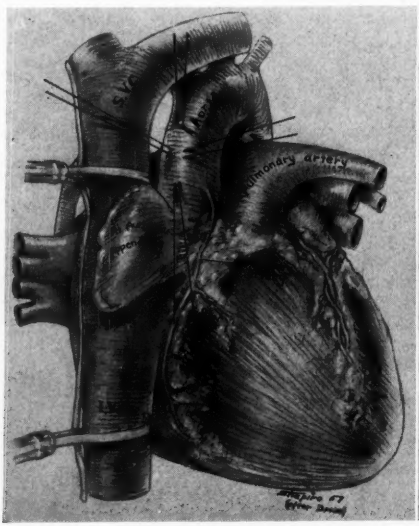

Fig. 4.

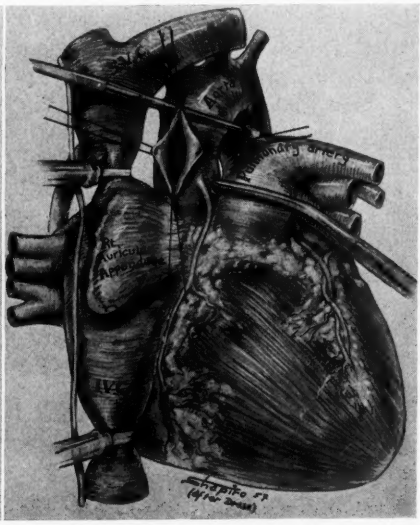

Fig. 5.

Fig. 4.—Following dissection of the root of the aorta, stay sutures are placed to facilitate the placement of the noncrushing clamp isolating the portion of the vessel which will contain the incision. Tapes have been placed on the venae cavae to provide inflow occlusion as needed. Right auricular tip is sutured laterally to auricle to provide exposure. The right coronary artery is exposed for protection during placement of the clamps.

Fig. 5.—During the procedure on the valve, the inflow tapes are tightened, the aorta is clamped distal to the incision, and the pulmonary artery is also clamped. In the retreat from the heart, the left heart and aorta are allowed to fill with blood by removal of the pulmonary clamp and release of the superior vena caval tape. When all air has escaped, the noncrushing clamp is applied to the incision and the cross-clamp on aorta instantly removed. The inferior vena cava is then released to restore full circulation.

For subvalvular stenosis, the valve is held open by a suitable retractor. The constricting ring is identified and grasped with the forceps. The anterior and right lateral portions are excised with a knife or scissors. Great care must be taken to avoid injuring the mitral valve which lies posterior and slightly to the left, and which can be injured where the constricting ring is attached to its ventricular surface. Escape from the heart is achieved by removing the clamp from pulmonary artery and superior vena cava. Blood soon wells up in the aorta and when all air is thought to have escaped, the noncrushing clamp is carefully reapplied to the incision. The transaortic clamp is now immediately removed and blood flow is re-established. The tape on the inferior vena cava is released after an additional few moments. The total occlusion time varies between 5 and 7 minutes.

The aortic incision is now meticulously closed with figure-of-eight interrupted sutures, a Gelfoam pad is placed on the suture line, and held in place by resuturing the pericardial-adventitial flap. The aorta here is friable and does not sew as readily as arch or descending aorta. The aortic closure is thus both difficult and nerve-wracking.

Pericardium is loosely closed, bilateral chest tubes are inserted for pleural drainage, the sternum is approximated with wire sutures, and the two thoracotomies closed with silk. No dressing is applied to the incision. During this portion of the procedure, the patient is being warmed with diathermy.

RESULTS

The results of operation in this series are shown in Table I. Of the 4 patients who had symptoms, the child with syncopal episodes prior to surgery as well as the one who complained of dizzy spells have had no symptoms since surgery and both are considered by their parents to have increased exercise tolerance. The other 2 who had had diminution of exercise tolerance have shown very definite increase in activity. Of the 4 patients who were thought to be asymptomatic prior to surgery, 3 remain so although one has had bouts of

TABLE I. ELEVEN PATIENTS WITH CONGENITAL AORTIC STENOSIS TREATED WITH OPEN TRANSAORTIC OPERATION

PATIENTS	SEX	AGE	SYMPTOMS	RESULTS
			Valvular Stenosis	
E. A.	F	10	None	Bicuspid valve; thrill gone; murmur decreased
T. M.	M	5½	Episodes of syncope	Bicuspid valve; thrill gone; less murmur; insufficiency minimal; no further syncope
J. R.	M	12½	None	Thrill gone; less murmur; moderate insufficiency; heart size unchanged; no symptoms
R. F.	M	12¾	Extertional dynpnea	Moderate insufficiency; febrile course; died of disruption aortic suture line on 27th day
C. D.	M	10	Exertional dyspnea, dizzy spells	Thrill gone; murmur decreased; all symptoms disappeared
M. H.	M	1 7/12	Excessive perspiration	Thrill gone; murmur decreased; moderate insufficiency; no change in heart size; no symptoms
C. S.	M	14	Decreased exercise tolerance	Thrill gone; murmur decreased; minimal insufficiency; exercise tolerance increased
C. E.	M	5 9/12	Decreased exercise tolerance	Thrill gone; murmur decreased; exercise tolerance increased
			Subvalvular Stenosis	
W. W.	F	12 8/12	Decreased exercise tolerance	Thrill gone; murmur less; died 5th day, tracheobronchitis
C. T.	M	26	None	Thrill gone; murmur less; occasional auricular tachycardia
W. B.	M	5	Exertional dyspnea	Died day of operation

paroxysmal atrial tachycardia for which he refuses medical care. The other has been noted to have a great deal more energy than preoperatively and, in retrospect, it is felt that he actually did have some impairment of his exercise tolerance.

The systolic thrill palpable in all patients along the upper right sternal border preoperatively disappeared following surgery. Likewise, the systolic murmur, although it did not disappear, was universally decreased in intensity, quality, and in the extent of transmission.

Aortic insufficiency in varying degrees developed postoperatively in 5 patients, 2 of whom had a bicuspid valve, one of whom died of another cause. This is considered minimal in 2 and of moderate severity in 2. Increases in pulse pressure ranging from 20 to 57 mm. Hg were observed in these patients, reflecting both a decrease in the diastolic pressure as well as an increase in systolic pressure. On the other hand, those patients who had no murmur of aortic insufficiency showed a maximum increase of 20 mm. Hg in pulse pressure. Despite the increased pulse pressure in these 4 patients, there has been no evidence of cardiac enlargement or congestive failure. The end result of their insufficiency remains to be seen, but it appears to date that the benefit from removal of the obstruction outweighs the burden of the regurgitant flow.

Objective laboratory evidence of regression of left ventricular enlargement and post-stenotic dilatation has not been found. However, only a little more than a year has elapsed since the first patient of this series was operated on. The electrocardiogram, in all instances, shows no significant regression in the amplitude of the left ventricular complexes nor in the activation time in the left precordial leads. On fluoroscopy, there has been no evidence of increase in heart size, although the amplitude of the pulsations has been increased in all patients. This again may reflect the increase in cardiac output in some, but is probably indicative of the aortic insufficiency in others. There has been no apparent change in the degree of post-stenotic dilatation; however, there has not been any increase in the size of the aorta.

One patient (C. S.) developed fever, anterior chest pain of a pleuritic nature, and pain in the left shoulder 3 months postoperatively. There was no evidence of pleural or pericardial friction rub or fluid, nor was there evidence of an infectious process elsewhere. This was interpreted as the pleural pericardial syndrome. The patient responded promptly to a short course of steroid therapy and has had no recurrence of his symptoms.

Of the 11 patients, 3 died. One (W. B.) died several hours after surgery of acute and intractable congestive failure following removal of a subaortic lesion. The specimen revealed that the mitral valve had been injured in the resection of the constricting collar. One patient (W. W.) died on the fifth postoperative day of tracheobronchitis. She had had a subvalvular stenosis relieved and at post-mortem examination it appeared that most of the obstructing ring had been removed (see Fig. 1). There was a small patent ductus arteriosus present, hitherto unsuspected, and there was extensive bronchiolitis. A third patient

(R. F.) ran a protracted febrile course despite extensive antimicrobial therapy. Blood cultures were sterile but he died suddenly on the twenty-seventh postoperative day of hemorrhage from a pseudoaneurysm at the aortic suture line. He had had signs of aortic insufficiency postoperatively (see Fig. 2).

DISCUSSION

The differential diagnosis between aortic valve and subvalvular obstruction remains most difficult, if not at times impossible. In the past it has not been considered that the clinical evaluation of the patient offers any findings that will allow this differential diagnosis. Some authors have held that the recorded arterial pulse tracing offers distinctive features, but most observers are not in agreement with this statement. At the present time, it is the opinion of most that ancillary investigations, such as left heart catheterization and angiocardiography, likewise will not enable this differential diagnosis to be established with any degree of certainty.

The factors that have been discussed in this paper are certainly not believed to be definitive in establishing anatomic diagnosis; however, we have found them helpful. Thus, the finding of the harsh, systolic murmur of maximum intensity in the third interspace, just to the left of the sternum or beneath the sternum, is considered to point toward the obstruction being at the subaortic level. The detection, where possible, of considerable dilatation in the very proximal portion of the aorta, that is, within the area of the sinuses of Valsalva, also points toward a subaortic stenosis. When both of these points are definitely noted, the diagnosis of subaortic stenosis is made. In this series, the diagnosis of subvalvular obstruction was made in 4 patients, and was correct in 3.

The establishment of etiology, especially in adults is also difficult. Unless the observer has personally followed the patient from the early years of life, he is not justified in stating that the lesion is of congenital origin. While it is possible that a mild congenital aortic valvular stenosis may, in the natural history of the disease, develop degenerative changes and calcifications, the vague history of a murmur in childhood by no means indicates that congenital aortic obstruction was the reason for the murmur. For this reason, it seems probable that many of the patients in the older age group recently reported to be of congenital origin,[3] in all probability had acquired forms of the disease.

In the past, aortic obstruction has been considered to be a relatively infrequent and benign lesion. However, recently it has been more frequently recognized. Those who have had the opportunity of following a series of these patients for a period of time have encountered sudden death as a not uncommon complication. The lesion can certainly not be considered benign. In our opinion, therefore, the finding of a clinical picture of significant aortic obstruction associated with definite and progressive hypertrophy of the left ventricle warrants surgical intervention.

As a result of our surgical experience in this series of patients, we are of the opinion that open operation upon the congenital aortic valve and subvalvular stenosis is technically feasible under hypothermia with circulatory occlusion.

Moreover, the pathology of the congenital obstructions is such that an excellent result can be achieved. The operation has definite risks and should be applied, at the present time, only in selected patients. The underlying theory that the pathology of congenital valvular obstruction will allow incision in the commissures with maintenance of competence of the cusps has been shown, we believe, to be generally true. However, in our application of this theory, aortic regurgitation has occurred sufficiently often to make us feel that the operator should err on the side of conservative relief of stenosis in order to prevent the undesirable occurrence of regurgitation. Aortic regurgitation unlike pulmonary regurgitation is a serious complication of surgery. Incisions into commissures, therefore, should be placed only in those commissures and only for such a distance that the operator feels quite confident that both adjacent cusps will remain competent. Most consistent results in the long run, therefore, will be achieved by the subvalvular type of obstruction, since in these patients, the risk of creating regurgitation does not exist and if care is taken not to injure the aortic leaflet of the mitral valve, relief of obstruction should be quite adequate.

Because of the precision required in the actual operative maneuvers for the correction of congenital aortic stenosis, it is our firm conviction that open direct vision technique is an essential component of the surgical therapy of this lesion.

SUMMARY

1. Eleven patients with congenital aortic obstruction were treated by direct vision transaortic surgical repair during circulatory arrest and hypothermia.

2. Eight of these patients had valvular and 3 had subvalvular stenosis. The pathology observed is discussed.

3. Recommendation for surgery depended on the clinical evidence of severe stenosis associated with left ventricular hypertrophy. Mild to severe symptomatology existed in 8 patients.

4. The results are encouraging but not uniformly ideal. The 8 surviving patients are considered to be improved, but slight to moderate aortic insufficiency exists in 4. Methods to prevent this complication in the future are discussed.

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(For Discussion, see page 190.)

THE SURGICAL TREATMENT OF STENOTIC OR REGURGITANT LESIONS OF THE MITRAL AND AORTIC VALVES BY DIRECT VISION UTILIZING A PUMP-OXYGENATOR

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OUR steadily increasing experience with a pump-oxygenator for the curative treatment of various congenital intracardiac malformations over the past years has created confidence and assurance about the well-being of patients during an interval of total cardiopulmonary bypass.

As a direct consequence of this knowledge, the obvious benefits of comparable visual operations have been extended to acquired or congenital lesions involving the aortic and mitral valves.

The total number of patients operated upon for these ailments is as yet small and the surgical techniques to a variable extent are still in a developmental phase. Moreover, in these operations, as in other new fields of surgical endeavor, unexpected problems have been encountered and unanticipated pathologic variations have on occasion demanded on the spot improvisations which have not always succeeded initially. However, much has been learned through this inevitably painful method of trial and error and even upon the basis of this limited experience it has become obvious that direct vision offers improved therapy for patients with aortic stenosis or mitral stenosis, especially those with more advanced states of valvular destruction. Moreover, for the first time, a definitive corrective procedure for those patients suffering from mitral regurgitation appears possible, and a promise of a similar improvement in the functional accomplishments for those afflicted with aortic regurgitation is offered by these techniques.

Consequently more and more patients with these lesions are being managed by use of total cardiopulmonary bypass and open cardiotomy. The surgical techniques developed and the results obtained so far for these various types of valvular lesions are presented herein.

The Heart Lung Machine.—An integral part of success in these operations has been the visualization of the valves. Utilizing a pump-oxygenator and total cardiopulmonary bypass the surgeon can carefully perform the necessary reconstruction. Normal body temperature has been maintained during the

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surgery and this serves a dual function. The incidence of cardiac arrhythmias is reduced and maintenance of the oxygenator blood at or a degree or two above the patient's body temperature effectively controls oxygen tension during oxygenation.

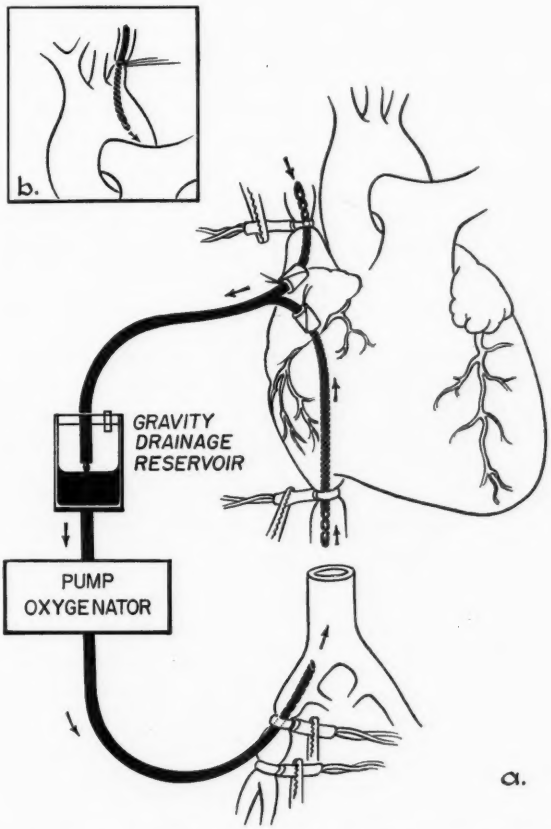


Fig. 1.—Technique of total cardiopulmonary bypass for open heart surgery. The venous blood is drained by gravity siphonage. For most patients the arterial blood is returned through a femoral artery catheter. *Inset:* Occasionally the subclavian artery is cannulated for this return.

All patients were operated upon utilizing the helix reservoir bubble oxygenator.[1-4] This instrument* is constructed of disposable polyvinyl plastic tubing and actuated by a Sigmamotor pump.† Our clinical experience with this pump-oxygenator involves over 400 patients. Despite its rather uncomplicated design, this apparatus has proved unsurpassed for the reliable and efficient maintenance of the cardiorespiratory functions for patients of any size.

*The helix reservoir bubble oxygenator components are made by The Phelan Manufacturing Company, 2029 Washington Avenue South, Minneapolis 4, Minn.

†Sigmamotor, Inc., 3 North Main Street, Middleport, N. Y.

Perfusion Technique.—We prefer to drain blood from the venae cavae by gravity siphonage into a venous reservoir.[5] From this collecting chamber the blood flows or is pumped to the oxygenator. The arterial return is completed via a thin-walled plastic catheter* inserted into the subclavian or femoral artery (Fig. 1). During the bypass interval, certain physiologic checks are maintained over the patient by a monitoring electroencephalogram and a continuous measurement of the systemic blood pressure is obtained via an internal mammary artery catheter. The flow rate is adjusted to keep the electroencephalogram normal and the systemic blood pressure normal or near normal.[6] One of the distinct advantages of an occlusive pump over the non-occlusive design has been the greater ease with which it is possible to maintain a normal blood pressure in the perfused subject without the use of vasoconstrictor drugs during the bypass interval. Most adult patients will have a normal blood pressure at a flow rate of 50 to 75 c.c./Kg. of body weight with such a pump. Infants and smaller children may require perfusion rates in the range of 75 to 125 c.c./Kg. body weight per minute to achieve this goal.

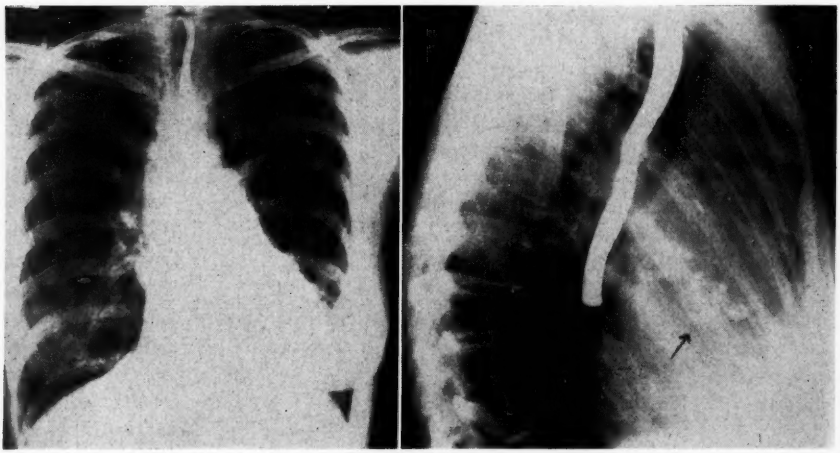


Fig. 2.—Calcific aortic stenosis. These preoperative roentgenograms are from the first patient (Case 1, Table I) operated upon utilizing the pump-oxygenator and retroperfusion of the coronary sinus. Note the heavy calcification in the aortic area evident in the lateral film.

When the size of the patient indicates that an oxygenating minute volume in the range of 2,500 to 5,000 c.c. may be needed, the double unit[4] is utilized together with the same pump (Sigmamotor TM-1).

AORTIC STENOSIS

Almost 2 years ago, in this clinic, a 39-year-old woman with severe acquired calcific aortic stenosis (Fig. 2) had a direct vision repair of the diseased valve utilizing a pump oxygenator in combination with retroperfusion of the coronary sinus.[7] This technique allowed for a precise, deliberate plastic re-

*C. R. Bard, Inc., Summit, N. J.

pair of the valve while providing the contracting myocardium with oxygenated blood. An excellent clinical result was achieved in this patient and she is living and working as a normal individual at this time. Since that initial case, retrograde perfusion of the coronary sinus has been utilized in 7 additional patients with lesions involving the aortic valve. The results of these operations are presented at this time together with pertinent comparative observations derived from our experience in 9 other patients with aortic valve disease in whom alternative techniques (elective asystole with potassium citrate or acetylcholine, temporary coronary ischemia) for direct vision aortic valve surgery have been tested in conjunction with total cardiopulmonary bypass at normal body temperature utilizing the pump-oxygenator.

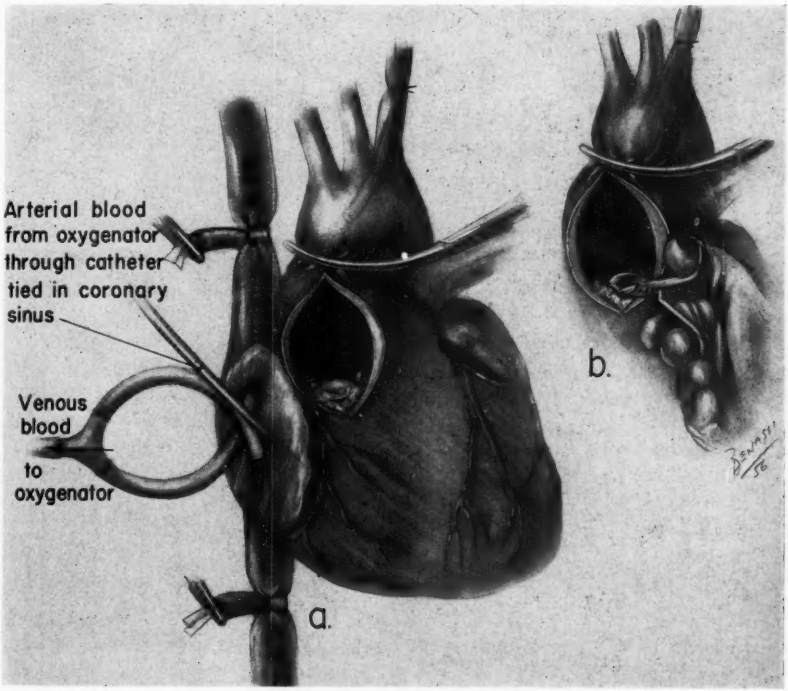


Fig. 3.—Technique for aortic valvuloplasty utilizing total cardiopulmonary bypass and retroperfusion of the coronary sinus to permit visualization of the aortic valve while maintaining the myocardial blood supply. *b*, The use of a heavy scissors or knife is sometimes necessary for valvotomy in the acquired lesions. This is the safest method for aortic valve surgery.

Method of Coronary Sinus Retroperfusion.—

The patient is connected to the pump-oxygenator in the usual manner (Fig. 1) and the perfusion is begun, totally bypassing the heart and lungs. The right atrium is opened and an appropriately sized plastic catheter (usually No. 14 to 16 Fr.) with a rigid plastic tip is inserted into the coronary sinus and secured in place with a purse-string suture (Fig. 3). On the basis of considerable laboratory experience,[8, 9] it is believed that the optimal perfusing

TABLE I. PATIENTS HAVING RETROPERFUSION OF THE CORONARY SINUS DURING TOTAL CARDIOPULMONARY BYPASS FOR AORTIC VALVULOPLASTY

CASE AND AGE (YR.)	LESION	RETROPERFUSION TECHNIQUE	DURATION (MIN.)		OPERATIVE PROCEDURE	PRESSURES		CLINICAL RESULT
			RETRO-PERFUSION	TOTAL BY-PASS		PREOP. AORTA L. VENT.	POSTOP. AORTA L. VENT.	
Case 1 39	Acquired calcific aortic stenosis	Separate retroperfusion pump (flow = 125 c.c./min.)	14	16	Created bicuspid valves because of obliterated cusps	—	—	Excellent
Case 2 28	Acquired calcific aortic stenosis	Separate retroperfusion pump (flow = 125 c.c./min.)	14	35	Commissurotomy	150/120 210/60	125/70 125/45	Died 2 days postop. from aortic insuff.
Case 3 52	Acquired calcific aortic regurg. and stenosis; mitral stenosis	Separate retroperfusion pump (flow = 125 c.c./min.)	13	18	Aortic valvuloplasty consisting of mobilization of leaflets by excision of synechiae in the sinuses of Valsalva and suture reconstruction; mitral commissurotomy	88/42 104/8	84/46 92/10	Excellent
Case 4 24	Congenital subvalvular stenosis	Y-connector in arterial limb	10	22	Incised the subvalvular diaphram	95/65 200/10	90/55 90/15	Excellent
Case 5 15	Congenital aortic valvular and subvalvular stenosis	Y-connector in arterial limb	32	45	Commissurotomy	80/15 175/15	—	Died, acute hemorrhage from tears in aorta
Case 6 5	Congenital aortic stenosis	Perfusion from reservoir at height of 50 cm.	2*	16	Commissurotomy	100/80 145/5	130/85 145/10	Excellent
Case 7 38	Acquired calcific aortic stenosis	Perfusion from reservoir at height of 50 cm.	2†	27	Commissurotomy	—	—	Excellent
Case 8 7 mo.	Congenital aortic stenosis	Perfusion from reservoir at height of 50 cm.	7	28	Commissurotomy	—	—	Died 8 hr. postop.; severe fibroelastosis of left ventricle

*The patient had 60 mg. of acetylcholine injected in retrograde catheter after retroperfusion started, then had 10 minutes of total ischemia with bradycardia of 8 beats/minute.

†The patient had 200 mg. of acetylcholine injected in retrograde catheter after retroperfusion started, then had 8 minutes of total ischemia with bradycardia of 30.

pressure for this retrograde coronary sinus flow is a mean of about 35 to 40 mm. Hg. We have achieved this perfusion pressure by several techniques, but the simplest method has been to perfuse the coronary sinus from a reservoir of oxygenated blood approximately 50 cm. above the heart. The blood volume in the reservoir is maintained by an inflow of arterial blood from the oxygenator (Fig. 4). Promptly after starting the retroperfusion, the ascending aorta is cross-clamped and, if an aortic valvuloplasty is to be performed, the ascending aorta is incised longitudinally. The diseased valve is then repaired under direct vision. When the valvuloplasty is completed, the aortotomy is reapproximated by application of a suitable vascular clamp and then carefully closed with a running silk suture. Any residual air within the aorta is expelled by the retrograde flow. As soon as the aortotomy has been closed, the retroperfusion is terminated and the cross-clamp removed from the aorta, restoring forward coronary perfusion.

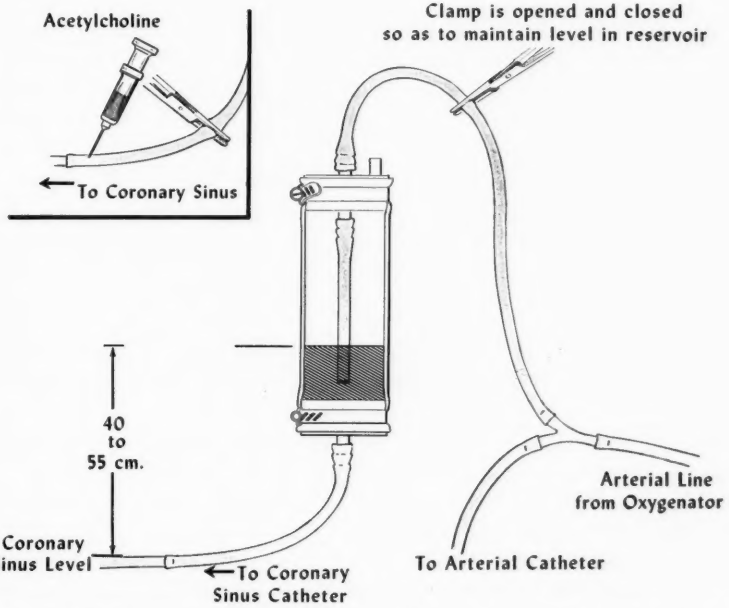


Fig. 4.—The most convenient method for controlling the pressure of the arterial blood retroperfusing the coronary sinus is to perfuse from a reservoir elevated 40 to 55 cm. above the heart *Inset:* Portrays one technique for retrograde arrest (see text for other details).

Recently (Table I, Cases 7, 8), we have used retrograde acetylcholine-induced asystole in combination with retroperfusion. After commencing the perfusion of the coronary sinus, acetylcholine is injected into the retrograde catheter until there is almost a complete standstill. The retrograde catheter is then clamped (Fig. 4, inset). This technique facilitates the arrest in patients with some degree of aortic insufficiency and also provides a still, dry field during the period that the valvuloplasty is being performed. Before the aortotomy is closed, the clamp is removed from the retrograde catheter. This allows arterial blood to

wash the acetylcholine from the myocardium and reinstitute good strong contractions before forward perfusion is restarted. In aortic valve lesions in which often some degree of insufficiency is present, it is very important that the left ventricle be beating at the time that forward coronary perfusion is restored otherwise irreversible left ventricular distention can occur. Two fatalities from this cause following potassium citrate asystole are summarized below.

An alternative method has been to add enough acetylcholine to the perfusing blood to maintain the arrest even though the retroperfusion continues. This procedure is deemed more feasible when a longer period of arrest might be needed such as in coronary artery surgery or aortic valvuloplasty for insufficiency.

Early in our clinical experience with retroperfusion, the coronary sinus was perfused with a separate Sigmamotor pump calibrated to deliver a predetermined flow of arterial blood to the myocardium. This technique was simplified subsequently by removing the pump and securing oxygenated blood directly from the main arterial limb of the oxygenator through a Y-connector. The pressure in this coronary sinus perfusing circuit was regulated by an adjustable clamp and monitored continuously by a strain gauge and Sanborn Twin-Viso recording apparatus. Although the two foregoing methods provided a proper coronary sinus flow, the technique of perfusing from a reservoir at 50 cm. has been the simplest and therefore the most satisfactory for clinical use (Fig. 4).

Surgical Technique for Aortic Valvotomy.—

Thoracotomy incision: The preferred incision for aortic commissurotomy under direct vision utilizing the pump-oxygenator has been a standard posterolateral thoracotomy through the bed of the right fourth rib with the patient in a straight lateral position and positioned on the operating table so that the kidney rest lies directly under the incision. Elevation of this rest after the chest has been opened gives excellent exposure to the ascending aorta. The caval cannulations and access to the coronary sinus for retroperfusion are satisfactorily accomplished with this approach. The arterial cannula has been inserted either into the right subclavian or common femoral arteries. The femoral arteriotomy is always repaired, and the subclavian arteriotomy is repaired in older children and adults.

The first patient operated upon by us for aortic stenosis, utilizing the pump-oxygenator for total cardiopulmonary bypass, had a bilateral anterior thoracotomy, but the exposure of the aortic valve was not improved by this incision over that obtained with the unilateral (right) thoracotomy and the likelihood of respiratory complications from the more extensive bilateral incision has been greater.

In several of the patients with congenital aortic stenosis where there was evidence of possible associated defects such as patent ductus arteriosus, pulmonary stenosis, or left superior vena cava, we have continued utilization of the bilateral thoracotomy to allow management of these associated lesions at the same time.

Aortotomy: After investigating several types of incisions in the aorta, we believe the most feasible to be a longitudinal hockey stick aortotomy which curves

posteriorly as the annulus is approached and thus ends up almost parallel with the annulus and just above it. This incision prevents extensions into the coronary arteries by inadvertent tears and also the flaplike opening thus provided improves the visualization of the aortic valve cusps.

Clinical results with coronary retroperfusion for aortic valvuloplasty: Eight patients had aortic valve disease. Three of these individuals had congenital valvular stenosis, one had a congenital subvalvular stenosis only, and in the remaining 4 patients the aortic valve was the site of acquired disease. The pertinent data upon these patients are listed in Table I.

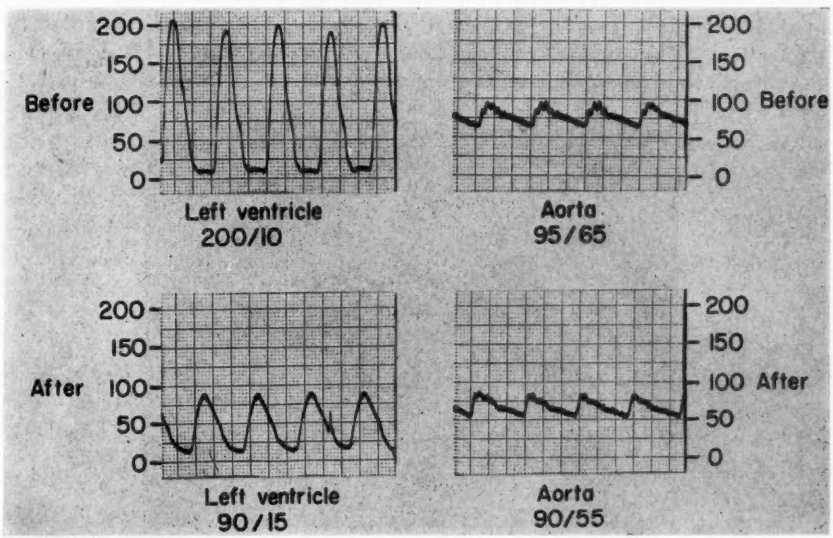


Fig. 5.—Subvalvular aortic stenosis (W. M., aged 24 years). The pressures measured just before and after direct vision excision of a subvalvular diaphragm through an open aortotomy. The aortic valve was normal (Case 4, Table I).

In the congenital valvular lesions, although the cusps were indeterminate in number, the leaflets were in all instances soft and pliable allowing a precise commissurotomy under direct vision. In all congenital valvular stenoses we have converted the valve opening into a bicuspid orifice. All the valves in the acquired disease group were heavily laden with calcium, which in some cases virtually obliterated the cusp commissure landmarks. Three of these had severe stenosis and the fourth had a predominant regurgitation with the valve fixed in a three-quarters open position. These valves were examined thoroughly at the time of surgery and if the commissures could be delineated they were incised carefully using either a scalpel or scissors. If the commissures were completely obliterated, two opposing incisions were made, thus forming a bicuspid valve which seemed to function very well (Case 1, Table I). Occasionally calcified spicules acting as struts between the cusp margins and the intima of the aorta within the sinuses of Valsalva were found and removed. In all cases dilators or the surgeon's fingers were passed through the

valve to ensure an adequate orifice and to aid in mobilizing the leaflets following the placement of these incisions. Pressures were recorded in the left ventricle and aorta before and immediately after valvuloplasty in 4 of the patients and these are listed in Table I. The improvement in the respective pressure gradients after valvuloplasty is apparent from this data. One of the optimal results was achieved in a patient (Case 4, Table I) who had a subvalvular diaphragm. A wide incision of this diaphragm completely abolished the 100 mm. Hg pressure gradient between the ventricle and aorta (Fig. 5).

Four of the 7 patients with aortic stenosis have shown excellent clinical improvement as a result of direct vision valvuloplasty and are living and well at this time. Likewise, the patient (Case 3, Table I) with predominant aortic regurgitation has achieved and maintained an excellent clinical improvement following direct vision mobilization and reconstruction of the aortic leaflets.

Fig. 6.—Patient with calcific aortic stenosis dying postoperatively of surgically induced regurgitation (Case 2, Table I); for such a rigid calcified valve, stenosis can be relieved with a greatly lessened risk of regurgitation by creating a wide bicuspid rather than a tricuspid aperture.

There were 3 deaths in this group of 8 aortic valvuloplasties. One patient (Case 2) had a severely calcified aortic valve and one of the commissural incisions created an intolerable insufficiency which contributed to his death 2 days after surgery (Fig. 6). Were we to operate now upon a patient with such a severely scarred and calcified valve in the light of more experience we would not attempt to restore a triangular orifice in such a case but rather create a wide bicuspid aperture which would relieve the obstruction without adding the considerable risk of aortic insufficiency.

A 15-year-old boy (Case 7) sustained an unfortunate complication when a transverse aortotomy just above the coronary arteries was utilized. During dilatation and excision of the subvalvular component of his stenosis, this circular incision was torn, completely transecting the ascending aorta. The aorta was reanastomosed during 32 minutes of retroperfusion and the heart continued to beat very well. Unfortunately 5 minutes of cardiac inflow stasis were required after termination of the retroperfusion to complete the repair

of leaks in the posterior suture line of the aorta and the combination of this anoxia together with hemorrhage caused the heart to go into irreversible ventricular fibrillation. This transverse aortotomy is not now recommended. The third death was in a critically ill infant (Case 8) who had a congenitally stenotic valve opened widely under direct vision. The operative procedure and immediate postoperative interval were uncomplicated. There was no postoperative aortic insufficiency. She died suddenly 8 hours after surgery and post mortem revealed severe endocardial fibroelastosis of the left ventricle which probably contributed importantly to her death.

Retroperfusion of the coronary sinus has also been utilized for the repair of three other types of cardiac lesions: complete transposition of the great vessels,[8] aortic pulmonary septal defect,[8] and ruptured aneurysms of the sinuses of Valsalva.[10]

Other Techniques for Exposure of Aortic Valve Area.—

At the present time there are several techniques available to the cardiac surgeon which permit direct vision surgery in the area of the aortic valve and ascending aorta.

Hypothermia: Hypothermia which has been used by Lewis[11] and Swan[12] and their associates appears to us to have two significant disadvantages; namely, a limited operative time in this area and increased irritability of the myocardium. Therefore, we have not utilized this technique for aortic valve surgery.

Potassium citrate asystole: In this clinic, retroperfusion of the coronary sinus in combination with a pump-oxygenator was first used on a patient in January, 1956, at which time no other oxygenator technique was available for exposure of the aortic valve. Retroperfusion has worked very well, but does entail the additional cannulation and purse-string suturing* of the catheter into the coronary sinus ostium. Thus, when the cardioplegic drugs became available and proved satisfactory for other types of intracardiac defects,[13-15] such as ventricular septal defects and tetralogy of Fallot, we felt that cardioplegia could be the answer to a simplified method for temporary aortic valve exposure. Our initial experience with cardioplegia for aortic valve disease was with potassium citrate. Both patients died on the operating table due to our inability to restart their hearts after only very brief periods of asystole. Summaries of these two chastening experiences with complete cardiac arrest in patients with advanced aortic valvular disease appear below.

CASE A: The recent symptoms in a 38-year-old man, leading to his referral for corrective surgery, were inability to work because of dyspnea and decreased physical strength associated with episodes of syncope upon mild exertion. A systolic murmur over the aortic area was first detected in 1946, while he was still in the Army. In 1952, he was hospitalized for this disability for the first time. In 1954, he developed subacute bacterial endocarditis which was successfully treated during a prolonged interval of hospitalization.

Physical examination disclosed a palpable thrill in the aortic area with a loud blowing systolic murmur of maximal intensity over the aortic valve area radiating up into the neck and in all directions. There was also a blowing diastolic murmur audible in the aortic area and transmitted down along the left sternal border of the sternum. The blood pressure was between 140/60 to 160/80 mm. Hg at various examinations.

*The use of a catheter equipped with a small Foley balloon makes the purse-string suturing unnecessary and is therefore simpler technically.

Roentgenography showed marked cardiomegaly due to left ventricular enlargement, and calcification of the aortic valve area was readily apparent. The electrocardiogram was abnormal due to marked left ventricular hypertrophy and strain.

To-and-fro murmurs and these other findings confirmed the diagnosis of calcific aortic stenosis and insufficiency.

Operation was undertaken March 27, 1957, by entering the chest through the bed of the right fourth rib with the patient in a lateral position. The ascending aorta was huge in size and a significant systolic thrill was present in it. There was also a marked diastolic thrill in the left ventricle.

The patient was linked to the pump-oxygenator in the usual fashion, bypassing the heart and lungs. The aorta was cross-clamped proximal to the innominate artery and 120 c.c. of 2½ per cent potassium citrate injected into the first portion of the aorta produced asystole. The ascending aorta was then opened, disclosing one normal commissure and two fused ones resulting in a valve orifice of 12 to 14 mm. in diameter. The exposure was excellent. The two fused cusps were carefully incised to the aortic annulus and the leaflets mobilized, resulting in what appeared to be an excellent valvuloplasty. Following this, the aortotomy was closed and the aortic cross-clamp removed after an arrest period totaling 11 minutes.

The left ventricle remained in complete arrest and was absolutely resistant to all attempts to restart it. Sequentially, massage, Adrenalin, calcium, and electrical stimulation were utilized without avail. The left ventricle continued to redistend unless emptied manually. After 90 minutes of perfusion, during which these efforts were continued, the pump-oxygenator was turned off.

Autopsy disclosed an excellent commissurotomy. Massive left ventricular hypertrophy was present. An incidental finding of interest was a functioning pheochromocytoma of the right adrenal gland.

CASE B: This patient was an 8-year-old boy who had had a heart murmur, known since 14 months of age. Cardiac catheterization and exploratory thoracotomy for a patent ductus arteriosus was carried out elsewhere at the age of 5 years. No ductus was found and the pericardium was opened and a very pronounced thrill was found in the right ventricle. The aorta was enlarged, actively pulsating and, together with the continuous thrill, resulted in the diagnosis of ruptured aneurysm of the sinus of Valsalva. The operative procedure was then terminated. Subsequent recatheterization and angiocardiography were interpreted as confirmatory of this diagnosis.

Physical findings at the time of admission were a blood pressure of 108/0 mm. Hg, a palpable thrill over the precordium, and a loud continuous murmur heard over the sternum and transmitted to the right and left and to the back.

On April 29, 1957, corrective surgery was carried out. Upon opening the pericardium a marked thrill was present in the right ventricle as previously described. This thrill appeared to originate from the aorta in the region of the right coronary artery origin and this fact, together with some aneurysmal dilatation in this region, led to the diagnosis of a ruptured aneurysm of the sinus of Valsalva. The aorta was much enlarged contrasted to the usual case of ventricular defect and this too seemed to be in favor of a ruptured sinus of Valsalva aneurysm.

After insertion of caval and arterial catheters, bypassing the heart in the usual fashion, the ascending aorta was cross-clamped just below the innominate artery and 50 c.c. of 2½ per cent solution of potassium citrate diluted in blood was injected into the proximal aorta. This resulted in a prompt asystole and a right ventriculotomy was carried out disclosing, instead of the anticipated ruptured aneurysm, a moderately sized (1.5 cm.) membranous defect in the ventricular septum with complete incompetence of the aortic valve. Sutures were placed across the ventricular defect and several were tied. Before completing tying the remainder, the clamp was removed from the aorta in order to re-establish the cardiac beat after a period of asystole of only 4 minutes. However, throughout the remainder of the perfusion lasting 2 hours, no left ventricular beat could be re-established.

Whenever an attempt was made to try to close the defect or close the right ventricle, the left ventricle would enlarge tremendously. To control this complication, a tourniquet was even passed around the aortic annulus and beneath the coronary arteries to allow coronary perfusion and to prevent left ventricular distention. This was without effect upon the completely paralyzed left ventricle. Eventually the ascending aorta was opened and an attempt was made to repair the aortic insufficiency by direct suture of the leaflets converting them into a bicuspid orifice. This was successful in controlling the regurgitation but it remained impossible to restore a heartbeat. However, the approach used in this patient for the management of the aortic insufficiency developed under the duress of necessity did contribute to the realization that direct surgical treatment of aortic regurgitation through valvular reconstruction was feasible.

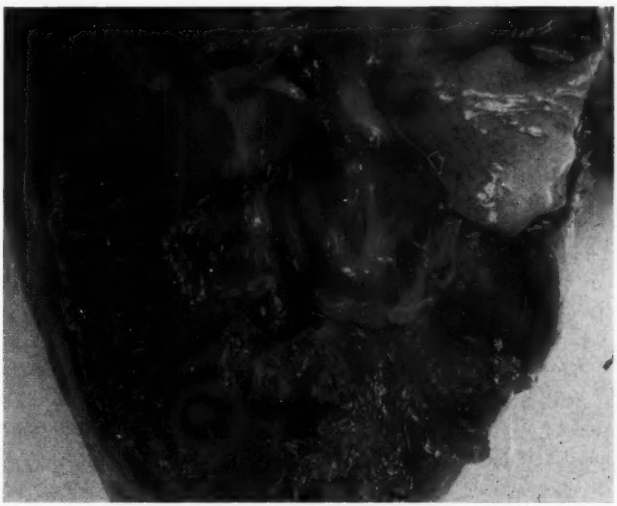


Fig. 7.—Close-up of the left ventricle of an infant (12 mo. of age) dying of congenital valvular aortic stenosis. Note the massive hypertrophy that has occurred during this brief period. The small size of the ventricular cavity also emphasizes one of the reasons these hearts are intolerant of a surgically induced aortic insufficiency.

Pathologic physiology: In advanced aortic valvular disease, the left ventricular hypertrophy is massive (Fig. 7) and doubtless exceeds the available coronary supply even though the latter may be entirely free of arteriosclerotic disease. This relative coronary insufficiency is the basis for the sudden deaths due to ventricular fibrillation characteristic of these patients. Moreover, it is not uncommon for the myocardium from hearts with advanced left ventricular hypertrophy to exhibit areas of ischemic necrosis. This latter finding is particularly liable to be present in the inner layers of the myocardium where the high left ventricular pressures constitute an added obstacle to the coronary circulation. If, in addition, there is superimposed some coronary artery obstructive disease as often happens in older patients with acquired lesions, it is obvious that the blood supply to these hearts often can be submarginal.

In such hearts it is understandable why potassium citrate, which gives a profound degree of relaxation of the cardiac musculature when perfused into the coronary circulation, is so dangerous. The problem appears to be primarily,

although perhaps not entirely, a mechanical one, namely inability to wash out the potassium citrate even though, as in these 2 cases, the perfusing head of pressure is raised to above normal levels.

After these 2 tragic experiences with potassium citrate, we have abandoned its use for aortic valve surgery. These 2 patients both had advanced aortic valvular disease with marked left ventricular myocardial hypertrophy. One patient had only 4 minutes and the other 11 minutes of arrest. In both instances, when the aortic clamp was removed restoring coronary perfusion to the paralyzed myocardium, the flaccid left ventricle distended severely, augmented by the slight degree of aortic insufficiency which is present in many if not most of these cases. The severe distention of an ischemic flaccid heart in combination with a poorly perfused hypertrophied myocardium led to irreversible fibrillation in both cases. Moreover, effective massage is usually difficult because of the massive concentric hypertrophy of these hearts. After these 2 poignant experiences with complete cardiac arrest in cases with advanced left ventricular disease, it was realized that ideally the heart should be beating during the valvuloplasty or before systemic blood pressure was restored to the aortic valve. The contracting left ventricle could then eject any blood that might flow back through slightly regurgitant valves when the clamp on the ascending aorta was removed.

Case B illustrates another lesson worthy of emphasis; namely, the inadvisability of arresting any heart before opening it to inspect the nature of the pathology. To date, we have utilized induced cardioplegia in over 100 patients and this patient is the only one in the series in which we have failed to observe this precaution. In this particular patient, we were misled by the fact that the external pathology appeared so typical of ruptured aneurysm of a sinus of Valsalva, together with the fact that potassium citrate asystole had worked well in 2 patients[10] with this pathology.

Total cardiac ischemia: Since aortic commissurotomy, in some patients at least, can be carried out under direct vision quite adequately within only a few minutes of actual working time, the possibility occurred to us early in this work that one might simply ignore the myocardial oxygen requirements of the bypassed heart for this brief period.

The theoretical attractiveness of this approach has been further enhanced by the many recent experimental studies and a number of human observations indicating that the heart is surprisingly tolerant to anoxia under these circumstances. In a recent patient, documented elsewhere,[15] we observed the heart to recover sinus rhythm spontaneously after 35 minutes of total ischemia without cardioplegia. Moreover, convalescence was uncomplicated by any arrhythmias. However, this patient, as do the experimental animals on which much of this information is based, initially had a good myocardial reserve.

This is obviously not true of patients with aortic valve disease. Thus, we have not been completely attracted, as previously stated,[7] to this approach of elective anoxia. However, we did try this method in just one 49-year-old woman with acquired calcific aortic stenosis. Commissurotomy was carried out

utilizing total cardiopulmonary bypass during only 5 minutes of complete myocardial ischemia at normal temperature. The heart continued to beat during this time and no cardioplegic drug was used. Despite the very short period of ischemia and an excellent commissurotomy, as determined by pressure determinations at surgery and confirmed later at autopsy, this patient died suddenly 36 hours after surgery and exhibited, at post mortem, extensive necrosis of the inner one third of the ventricular myocardium.[16]

Use of acetylcholine asystole: We have had experience with 6 patients with aortic valve disease utilizing total cardiopulmonary bypass at normal temperature together with acetylcholine induced asystole (Table II).

TABLE II. CORRECTION OF AORTIC STENOSIS UTILIZING TOTAL CARDIOPULMONARY BYPASS WITH ACETYLCHOLINE* ASYSTOLE

CASE AND AGE (YR.)	TYPE OF STENOSIS	MINUTES DURATION OF		ARRHYTHMIAS	RESULT
		TOTAL BYPASS	ARREST		
Case 1 5	Congenital valvular	12	3	Ventricular fibrillation†	Excellent
Case 2 22	Congenital valvular	20	7	None	Excellent
Case 3 11	Congenital subvalvular	12½	7	Ventricular fibrillation†	Excellent
Case 4 6 mo.	Congenital valvular	13	5	Cardiac arrest 6 hr. postop.; good immediate recovery	Died 48 hr. postop.; no clear-cut cause of death; debilitated preop.
Case 5 7	Congenital valvular	17	6	Ventricular fibrillation†	Excellent
Case 6 49	Calcific aortic stenosis	62	53	Ventricular fibrillation†	Severe aortic insufficiency created by initial commissurotomy which then was corrected by valvuloplasty. Died 2½ days postop. of left ventricular failure due to myocardial necrosis

*10 mg/Kg. body weight.

†Developed shortly after restoration of coronary arterial flow; easily defibrillated with electric shock and pump-oxygenator support.

In general, this experience has been quite satisfactory and certainly if cardioplegia alone is to be used in these hearts with massive left ventricular hypertrophy, acetylcholine appears to be somewhat safer than potassium citrate.

Acetylcholine often does not completely arrest the heart immediately and allows it to beat slowly for a variable period during the cardiac ischemia before complete asystole occurs. However, the myocardium in the acetylcholine-arrested heart is very responsive to external stimuli such as massage and thus the beat may be quickly restored. This obviates the very dangerous complication of ventricular distention encountered with the profound relaxation of potassium citrate arrest. The technique of using acetylcholine is not without some danger, however, for this slowly beating ischemic heart may be utilizing

more energy than the completely stilled heart. The much greater incidence of ventricular fibrillation in these hearts (Table II) in comparison to those with retrograde coronary perfusion is perhaps significant in this regard. For these reasons, the period of ischemia utilizing acetylcholine should be brief. It does appear from the experience in this small clinical series that acetylcholine cardioplegia can be used safely for aortic stenosis if this period of ischemia is no longer than 10 to 15 minutes, the myocardium is not greatly hypertrophied, and the cardiac reserve reasonably good.

However, Case 6, Table II, illustrates the fact that it is often not possible to be certain a priori of the duration of any intracardiac procedure. In this man the initial commissurotomy resulted in an obvious aortic insufficiency. In the subsequent interval, it was possible to obtain an excellent reparative result upon the valve preserving an adequate orifice and correcting the insufficiency (Fig. 9) but the cardiac ischemia was severe. It is likely that retrograde perfusion during this interval might have made the difference between success and failure in this case.

Current Procedure for Aortic Valve Lesions.—

At the present time we are using total cardiopulmonary bypass together with acetylcholine asystole for the patients with congenital aortic stenosis who as a group are much better operative risks.

In all patients with acquired aortic lesions and in those with congenital lesions in whom the valve leaflets are severely diseased, the ventricular myocardium is greatly hypertrophied, and a longer period is contemplated for the valvuloplasty, we believe retrograde perfusion of the coronary sinus as an adjunct to the cardiopulmonary bypass is the safest procedure.

AORTIC REGURGITATION

Insufficiency of the aortic valve has presented a formidable challenge to surgical treatment. The palliation afforded to certain far-advanced cases by insertion of a Hufnagel valve[17] into the thoracic aorta has been of definite value. However, quite obviously something more curative is necessary.

The thought has been advanced by some that nothing can be done for this lesion until a completely satisfactory prosthetic valve is available and one which can be inserted so as to replace the diseased valve and lie proximal to the coronary artery ostia. We would disagree with this philosophy for at least two reasons. First, such a completely satisfactory valve is not likely to come about until a greater familiarity with the pathologic anatomy has been acquired by surgeons working within this area under direct vision. Second, if experience elsewhere can be taken as any guide, once this familiarity has been acquired it will be likely that methods for reconstruction of diseased valves will evolve and a completely artificial valve may not be needed nearly as often as current predictions suggest. This sequence has evolved recently in respect to the mitral valve.

Much of our small experience to date in regard to the development of a direct reparative procedure for aortic insufficiency has been an outgrowth of commissurotomy procedures for aortic stenosis in which a significant or obviously intolerable degree of insufficiency was produced inadvertently.

Pathologic Anatomy of Aortic Regurgitation.—

One very favorable anatomic aspect of the primarily aortic insufficient lesion that has impressed us, when these hearts were studied in the fresh state, was the suppleness of the leaflet tissue together with usual absence of calcium. This is in marked contrast to the usual pathologic change found in those patients with acquired aortic stenosis. There is a parallel here with the mitral valve where, in regurgitant lesions, the pathologic alterations in the leaflets per se are frequently much less severe than those found in stenosis, yet the surgical treatment of regurgitant lesions has lagged far behind. The reasons for this are, of course, clear. Stenotic valvular lesions are often successfully widened by blind techniques whereas direct vision seems essential for a successful valvuloplasty for

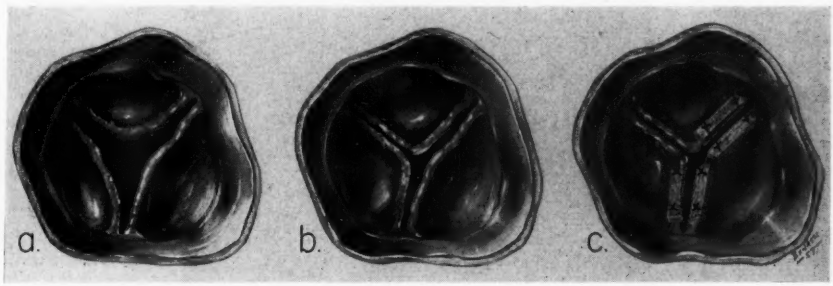


Fig. 8.—Technique for the direct vision surgical correction of aortic insufficiency of the primary type.

a, The usual pathology is portrayed. There is a shrinkage of the cusps due to moderate thickening and retraction, but calcium is usually absent and the leaflets remain flexible. Annular dilatation, except in the syphilitic patients, is usually not prominent. As a consequence of these changes, coaptation of the cusps during diastole is imperfect.

b, Our concept of treatment is to obliterate one commissure entirely by silk sutures leaving a wide bicuspid opening.

c, Any actual loss of cusp substance or residual failure of the cusps to coapt completely is corrected by the addition to the leaflet margins of pledgets of compressed polyvinyl sponge (Ivalon) as needed.

This technique of repair is also applicable to the regurgitation that may follow procedures to relieve aortic stenosis.

insufficiency. But beyond that, it is predictable that the results of surgical correction of insufficiency either of the mitral or aortic valves is likely ultimately to surpass that possible for stenotic lesions because of the better cusp or leaflet tissue remaining with which to work.

In the nonsyphilitic patients with a rheumatic etiology for their aortic insufficiency, annular dilatation has not appeared to be a very significant element. Rather the leaflets, although often only slightly or moderately thickened, are still very pliable but fail to meet together tightly enough because of thickening and a tendency for the free edges of the cusp to roll or curl back (Fig. 8, *a*). These observations have constituted the basis for a valvuloplasty procedure described below.

A Surgical Technique for the Correction of Aortic Insufficiency.—

The concept that we have developed (and on the basis of our to-date limited experience it appears to have merit) is to convert by suture the normally tricuspid aortic valve into a bicuspid orifice and reinforce and give additional support if necessary to the lips of this bicuspid opening by suturing to its edges small pledgets of compressed polyvinyl sponge (Ivalon) (Figs. 8, 9). It is

possible to convert the valve mouth to a bicuspid aperture by interrupted stitches of silk. This adds significant support to the leaflet tissue without the concomitant creation of stenosis. The addition of these Ivalon strips corrects the tissue deficiency resulting from the curled cusp margins and the added weight of the Ivalon also contributes to their tighter closure during diastole. A favorable observation noted at surgery in our patients is the fact that these slightly or moderately thickened cusps hold fine silk stitches well and much better than would be true for the paper-thin normal cusps.

Fig. 9.—Aortic valve from patient in whom aortic valvuloplasty was carried out for a surgically induced aortic insufficiency (Case 6, Table II). In this man, operated upon for calcific aortic stenosis, the opening of all three commissures resulted in a severe regurgitation. This was corrected completely by the valvuloplasty procedure portrayed in Fig. 8, leaving a widely patent and competent aortic aperture. The Ivalon pledget sutured to the leaflet margin covers the suture line obliterating the third commissure (see text for details).

*Report of Cases.—**

The clinical application of these observations is in the developmental stage at this time. Only 3 patients have had some attempt made at correction of a significant degree of aortic insufficiency. These presented concepts have evolved from our experience to date.

The first patient operated upon (Case 3, Table I) has been the only successful result to date. Progressive incapacitation due to fatigability and both right and left cardiac decompensation were the indications for surgical therapy in a 52-year-old lady whose operation was carried out on May 23, 1956, utilizing coronary retroperfusion in addition to total cardiopulmonary bypass. This patient's valve lesion was a mixture of mild stenosis and considerable regurgitation of rheumatic etiology. The cusp leaflets were fixed in an approximately

*Since submission of this report the first patient with pure aortic insufficiency has been operated upon. O. B., aged 45 years, had had rheumatic fever at 6 years of age. He remained well until age 30 when the first symptoms of heart disease were manifested. Deterioration in the year immediately prior to surgery had been rapid with acute pulmonary edema upon effort, angina pectoris, and claudication, massive cardiomegaly, a loud blowing diastolic murmur in the aortic area, and a blood pressure of 220/50/0 mm. Hg.

Operation was undertaken Jan. 8, 1958, and the aortic valve pathology and its method of repair was nearly identical to that portrayed in Fig. 8. The interval of pump-oxygenator support was 48 minutes and the heart was retroperfused for 25 minutes without arrest or any arrhythmias, despite the very poor cardiac reserve. Convalescence was uncomplicated. The diastolic murmur and water-hammer pulse disappeared completely. His blood pressure fell immediately too and has remained at $\frac{120 - 130}{75 - 85}$ mm. Hg. All evidence suggests a complete correction of the regurgitant leak in this man.

three quarters open position, in part due to adhesions across the sinuses of Valsalva. These were freed with the scissors hereby restoring considerable mobility to the leaflets. Nevertheless, although some improvement had resulted, significant insufficiency still remained due to a failure of the leaflets to meet satisfactorily in the midline (this is demonstrated in Fig. 8, *a*). Two mattress stitches were placed as in Fig. 8, *b* with obvious improvement. No polyvinyl sponge was utilized to supplement the area of the cusps in this patient. The proximal aorta was considerably dilated. Therefore in closing the aortotomy a generous elipse was excised from the aortic wall in order to bring about a "snugging up" effect upon the annulus.

Our second experience with this problem occurred in the child already described in Case B. Potassium citrate arrest was used. Preoperatively, the patient was thought to have a ruptured aneurysm of Valsalva. Actually he had a ventricular septal defect with a grossly insufficient aortic valve. Although this case terminated unsuccessfully, we were gratified by the degree of improvement induced in this very severe case of aortic regurgitation utilizing mattress stitches of silk placed again as shown in Fig. 8, *b*. This experience emphasized to us that a definite accomplishment in thwarting the aortic leak had been achieved.

The third patient, reported in Table II as Case 6, was a 49-year-old man with clinically far-advanced disability due to calcific aortic stenosis. This apparently had evolved after a severe, febrile illness in childhood.

Right and left heart catheterization carried out 2 months prior to surgery disclosed the following pressures (mm. Hg): left ventricle 180/28, femoral artery 104/51, and pulmonary artery 75/36. No pressure gradient existed across the mitral valve which denied the existence of significant disease at that site. These studies supported the diagnosis of severe aortic stenosis with chronic left ventricular decompensation. Calcium was plainly visible and in considerable quantities in the aortic valve area in his chest roentgenogram.

Corrective surgery, utilizing a right thoracotomy and total cardiopulmonary bypass, was undertaken. After cross-clamping the ascending aorta and just prior to opening it, the heart was arrested with a proximal intraaortic injection of 500 mg. of acetylcholine. On exposure of this area we noted the valve was severely stenosed and had a rigid eccentric slitlike orifice, 4 or 5 mm. in length, located at the one commissure. The other two commissures had been completely fused by heavy deposits of calcium. Vision and exposure were excellent. We carefully incised the two obliterated commissures with the knife and scissors opening them widely, well out to the annulus. These maneuvers restored the normal tricuspid aperture. When the aortotomy was closed, the heartbeat came back promptly after restoration of coronary flow and the heart and lungs were bypassed for 21 minutes. However, it was apparent at once that although good relief from the stenosis had been obtained, a very pronounced diastolic thrill now existed over the left ventricle. Moreover, the heartbeat during the succeeding 5 to 10 minutes became much weaker and arrest appeared imminent. Therefore the pump-oxygenator was turned on and the cardiopulmonary bypass restored. The aortotomy was reopened. This time the valve was converted into a bicuspid one by sewing up one commissure completely with interrupted 3-0 silk mattress

stitches as shown in Fig. 8, *b*. Again the aorta was closed after this second bypass interval of 18 minutes. The heart had gone into ventricular fibrillation and electrical shocks were required to restore rhythmic contractions. The diastolic thrill in the left ventricle seemed less evident to palpation but was definitely still present. In confirmation of this imbalance, the cardiac contractions became progressively more feeble. Therefore we elected to reopen the aorta once again. Our reappraisal painstakingly carried out revealed the cause of continuing insufficiency. These bicuspid leaflets which had been formed by the sutures were inadequately coapting due to the loss of substance and curling of the margins present. Compressed Ivalon (6 to 1) was fashioned in the form of a small pledget and sutured to the edge of the deficient leaflet using mattress stitches of silk (Fig. 9). To the eye this gave a far better correction of the valvular insufficiency. The heart had again gone into ventricular fibrillation during this third period of anoxic arrest of 14 minutes' duration and was once more defibrillated. This time it took over at once and established an excellent beat. The left ventricular diastolic thrill had completely disappeared. Significantly too, and in confirmation of this was the fact that the patient achieved and maintained a near normal blood pressure without pump-oxygenator support. For the second and third aortotomies no acetylcholine was used. Thus, the heart was in anoxic asystole during both of these intervals. The aorta was cross-clamped a total of 53 minutes and the total perfusion duration was 61 minutes at a perfusion rate of 3.3 L. per minute (55 c.c./Kg. per minute).

Postoperatively, despite this complicated procedure, his condition appeared surprisingly good. He awakened immediately, was alert, and had a normal systemic blood pressure. The pulse rate was only 80 to 100 per minute. The electrocardiogram was bizarre. It appeared to be made up entirely of ventricular extrasystoles. Because of the slow rate and good blood pressure no specific therapy was instituted for this arrhythmia. On the following morning the electrocardiogram seemed much improved revealing a return of sinus rhythm, and a disappearance of the ventricular extrasystoles. Other evidences of severe myocardial depression persisted, however.

His clinical progress during the next 2 days appeared to be quite uncomplicated until rather suddenly (within one hour) on the third postoperative day he developed progressive dyspnea, orthopnea, and pulmonary edema. Despite rapid digitalization and tracheotomy he died. Autopsy disclosed a gratifying reconstruction to the valve (Fig. 9). Both the stenosis and regurgitation seemed to have been corrected. Death was due to left ventricular failure secondary to widespread areas of focal necrosis in the myocardium.

Technical Considerations in Aortic Valve Reconstruction.—

These cases portray the development of some of our techniques for aortic valvuloplasty. While much undoubtedly remains to be learned we have been encouraged by the extent to which these diseased and distorted valves can be restored to function without dependence on a completely artificial valve which moreover is as yet unavailable in a workable and tested form. Several technical considerations derive from this experience and are deemed worthy of

emphasis. First, in aortic stenotic valves of the acquired type which are severely distorted and rigid from scarring and calcification, the operator is naturally tempted to open all three commissures. This is unwise because of the likelihood of creating too much insufficiency. It seems preferable to relieve the valvular obstruction by limiting the commissuroplasty to establishment of a bicuspid aperture. Second, if necessary, any loss of substance can be replaced by suturing pledgets of compressed Ivalon or nonwettable Silastic plastic to the cusp edges. We believe ample evidence now exists from the congenital lesions to indicate that bicuspid valves will provide good function once the element of stenosis has been relieved. Our first patient with aortic stenosis who was operated upon under direct vision 2 years ago had a valve heavily laden with calcium. It was converted into a bicuspid valve of necessity. Not until later experiences did we realize the value and importance of this concept. To be sure for those stenotic lesions with lesser degrees of destruction the creation of a tricuspid orifice is probably preferable if it appears that the leaflets are supple enough to regain their function. This decision as to which type of precedure to try is best made after the valve is visualized. At all times it is reassuring to know that with the pump-oxygenator bypass technique considerable opportunity is provided for correcting any inadvertently induced aortic insufficiency, as well as for dealing with the many pathologic variations encountered, and even for insertion of an artificial valve.

These techniques cited above in the management of aortic insufficiency created by attempts at relieving aortic stenosis have definite applicability to the direct surgical approach to primary aortic insufficiency. In summary they are: creation of a wide bicuspid orifice by suturing one commissure and overcoming any loss of substance by addition of pledgets of compressed Ivalon to these cusp edges as portrayed in Fig. 8.

Others have suggested that aortic insufficiency can be managed by reducing the circumference of the annulus by circumferential plication or resection of a portion of the annulus in the noncoronary area. Although we rather doubt that either of these approaches will be commonly useful and may well create new technical problems we believe they, particularly resection of the annulus, should be kept in mind as supplementary measures.

MITRAL REGURGITATION

For almost 10 years now, stenotic lesions of the mitral valve have been satisfactorily treated by well-known surgical measures involving finger fracture supplemented in some patients by commissural incisions. However, the regurgitant lesions of the mitral valve, despite their clinical importance as a major cause of cardiac disability, have continued to challenge cardiac surgeons and numerous and diverse surgical approaches have been described. Many ingenious devices have been inserted into the mitral orifice in an attempt to diminish the regurgitant flow. Most of these techniques have been directed at the posterior commissure for this is the usual site of reflux; the anterior one is less frequently insufficient because of the greater reserve of leaflet tissue in that area.

Substances such as pericardial tubes,[18] vein grafts,[19] and tendon grafts[20] placed across the posterior leaflet to diminish the regurgitant channel have usually eventuated in shrunken fibrotic struts. A rigid Ivalon sponge,[21, 22] a mobile Ivalon sponge sling,[23] and a Lucite baffle[24] have also been placed in the mitral orifice but with limited success.

Approximation and elevation of the posterior aspect of the mitral valve have been attempted by the use of pericardial strips,[25] vein slings,[26] silk sutures,[27, 28] artificial cusps formed of nylon,[29] inverted veins,[30] and pericardium.[31]

Davila, Glover, and associates[32, 33] have advocated the placing of a circumferential suture around the mitral annulus to narrow the regurgitant area.

Present Approach.—

The large variety of operations proposed for the correction of mitral insufficiency confirms to some extent the general ineffectiveness of many of these techniques. Nevertheless, an analysis of these experimental and clinical endeavors has brought additions to our basic knowledge about this lesion. Several of the techniques reviewed above seem sound in theory. Perhaps therefore a major reason for their lack of uniform success arose from the obvious consequences of their having been done as blind procedures. Certainly the ability to observe the diseased valve during surgery should self evidently improve the surgical results by assuring that the particular reparative procedure be performed which fits the specific lesion being looked at functionally. The development of the pump-oxygenator as a safe and effective tool has now made such open operations upon the mitral valve both possible and feasible.

Pathologic Physiology of Mitral Regurgitation.—

Mitral insufficiency may result from varying combinations of two primary factors: (1) an absolute loss of valve substance from cicatricial retraction and shrinkage of leaflet tissue and/or chordae tendineae, and (2) dilatation of the annulus fibrosus. Furthermore, these two factors are interrelated to the extent that severe insufficiency may result from compensatory left ventricular dilatation secondary to an initial deficiency—not necessarily severe—in the valve substance.

Moreover, for this same reason, mitral insufficiency once established, tends inherently to progress. The regurgitant leak into the left atrium begets a compensatory left ventricular enlargement to maintain the cardiac output; and this, by further stretching of the annulus, produces an ever greater mitral leak. In confirmation of this is the clinical cardiologic observation that regurgitant lesions of the mitral valve are tolerated progressively less satisfactorily with time than are stenotic ones.

Surgical Concepts and Technique.—

The mitral valve has been visualized in all patients utilizing the helix reservoir bubble oxygenator and the Sigmamotor pump for the necessary interval of total cardiopulmonary bypass.

Elective asystole has not been utilized since it has appeared to be disadvantageous for these procedures to have the ventricles in repose in contrast

to the experience in certain of the complex forms of congenital heart disease where it has been most helpful. In several of the patients there was a copious influx of blood into the operative field from an incompetent aortic valve. We have managed this by intermittent aortic occlusion as previously described.[34]

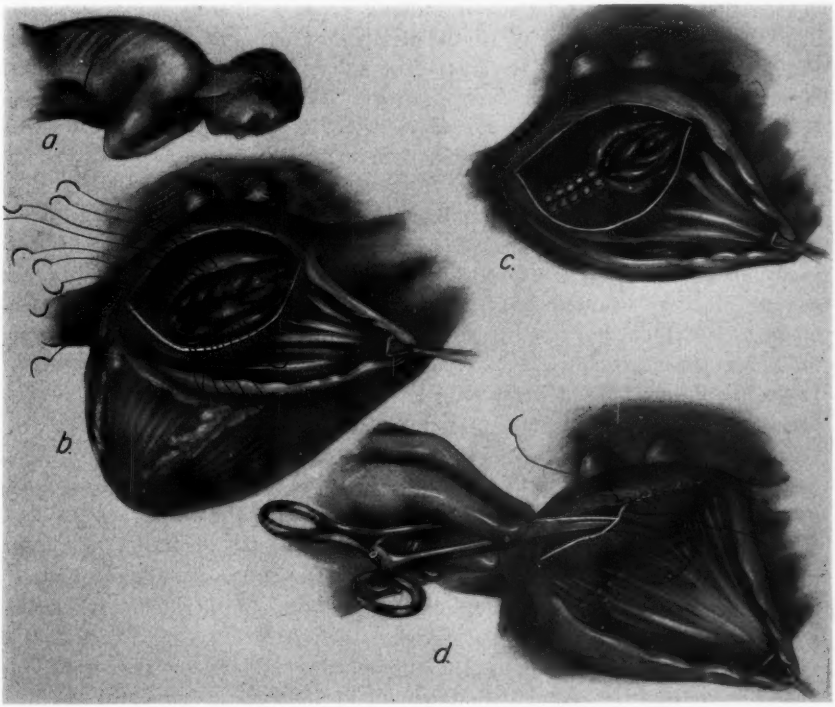


Fig. 10.—Correction of mitral regurgitation by direct vision annuloplasty.

a, Standard posterolateral right thoracotomy incision through the bed of the fifth rib.

b, Placement of mattress stitches of heavy silk in annulous fibrosus of incompetent portion.

c, These stitches are tied tightly over pillows of compressed polyvinyl sponge to prevent any cutting out before the approximated annulus has healed securely.

d, After valve competency has been restored, the usual precautions against retained air in the left ventricle are necessary as the atriotomy is closed.

Annuloplasty is utilized in those patients where the regurgitation is due in part or entirely to annular dilatation.

Surgical incision: One of the important elements of success with all 5 of these patients has been the choice of a right posterolateral thoracotomy incision to approach the left atrium. Unquestionably the best exposure of the mitral valve is obtained through a left atriotomy performed from the right thorax. This anatomic consideration is more easily appreciated when it is recognized that the left atrium is actually posterior rather than sinister. With the patient in a right lateral position, the thoracotomy is performed through the bed of the right fifth rib. The venae cavae are cannulated in the usual manner through the right atrium. Through a purse-string suture, a third

cannula is placed into the right atrium in order to aspirate the coronary sinus blood before it passes to the lungs and upon return obscures the operative area in the left atrium. The arterial cannula is usually placed in the right common femoral artery. After the perfusion is begun, the wall of the left atrium is incised longitudinally near the interatrial groove, anterior to the insertion of the pulmonary veins (Fig. 10). This opening is readily made without the need for any dissection of the interatrial sulcus, because the left atrium has been of giant proportions in these patients. This atrial incision provides excellent exposure of the entire mitral valve region. Under direct vision with the left heart essentially free of blood and with the left ventricle beating, the pathologic lesion can be carefully assessed by inspecting the leaflets, their commissures, and the chordae tendineae. Often, if the operative field is unusually dry due to a normal aortic valve we have found it helpful to temporarily clamp the catheter aspirating the coronary sinus blood. This provides enough blood to evaluate valve function. Any stenosis present at the commissures is evident and readily correctable with the scissors. Fused chordae tendineae, when present, can be separated. The area of insufficiency has been frequently located at the posterior pole (Cases 1, 2, 3), but was also found to arise anteriorly (Case 4) and even involve an entire leaflet (Case 5).

Method of annuloplasty: This technique of suturing the mitral annulus under direct vision with silk suture was first tested in the animal laboratory. The procedure was well tolerated despite the fact that the normal canine valve is an unusually delicate, paper-thin structure and thus a poor imitation of the diseased regurgitant valve in man. Clinically, when the annulus was greatly enlarged (Cases 1, 2, 3, 4), annuloplasty was performed above the insufficient area by placing interrupted mattress sutures of heavy silk (No. 2, with double-armed swedged-on needles) in the annulus fibrosus. These were tied down over pillows of compressed Ivalon sponge to prevent any possibility of their cutting out before healing was complete. These stitches approximate the annulus and hence reduce orificial circumference. Occasionally as many as seven or eight interrupted mattress sutures have been placed in order to eliminate the regurgitant jet. This beating heart with its tonic myocardium has been very helpful for evaluating the regurgitation tendency during the annuloplasty. The blood ejected by the contracting left ventricle continues to delineate the area of insufficiency and indicates when the operative repair is satisfactory. As the annulus is approximated, the surgeon may observe exactly how much additional plication is required for the best function. In each of the 4 patients with pathologic changes, characterized primarily by annular dilatation (Cases 1 to 4), it was possible to reduce the annular length enough to correct the regurgitation and still leave a mitral orifice of normal size (2 or 3 fingerbreadths), i.e., no element of stenosis was introduced by the surgical correction.

In placing these stitches in the annulus, generous bites of this tough tissue are taken and this fact together with their being tied over pledgets of Ivalon

makes any late reopening, before healing has occurred, appear unlikely. In placing these stitches in the annulus from inside the left atrium, one is working close to the coronary artery directly opposite and just outside of the auricular wall. This technical consideration should be kept in mind so as to avoid any compromise of this vital vessel, particularly at the anterior pole. After annuloplasty is completed, the atriotomy is closed with a running everting silk suture, and the perfusion is terminated.

Insertion of prosthetic valve leaflet: In Case 5, despite a giant left atrium and advanced left ventricular enlargement, the annulus of the mitral valve was of normal circumference. The valve was markedly insufficient because of virtually complete disappearance of the mural (posterior) leaflet by cicatricial retraction. Several plicating mattress stitches of silk were placed in the posterior annulus, and tentative approximation of these produced stenosis,

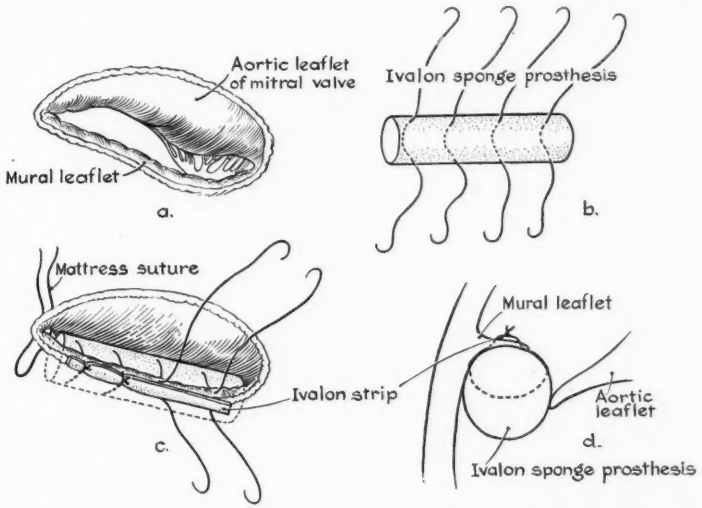


Fig. 11.—Correction of mitral regurgitation by direct vision insertion of a prosthetic leaflet.

a, This procedure is used alone or with annuloplasty where loss of valve substance is prominent. In this case the entire mural (posterior) leaflet is scarred and retracted. The aortic (anterior) leaflet is of good quality. The annulus fibrosus is of normal circumference.

b, Silk stitches (No. 2) with swedged needles are passed through an appropriately sized cylinder of compressed (3:1 or 4:1) polyvinyl sponge near its equator.

c, The mitral valve is viewed from above through the atriotomy incision and these needles are introduced from below upward. For each stitch, one needle is brought through the annulus fibrosus and its mate slightly adjacent as a verticle mattress stitch. Each of these stitches is then securely tied over a strip of polyvinyl sponge.

d, Portrays how this prosthesis restores competency without producing stenosis by providing a firm buttress against which the aortic leaflet may close.

without correcting the regurgitation, and so they were removed. Clearly the abnormal leaflet had to be replaced by a space-occupying prosthesis which could provide sufficient substance and against which the flexible aortic (anterior) leaflet could coapt during ventricular systole. At the same time stenosis should not be produced. This eventuality had been foreseen in our previous

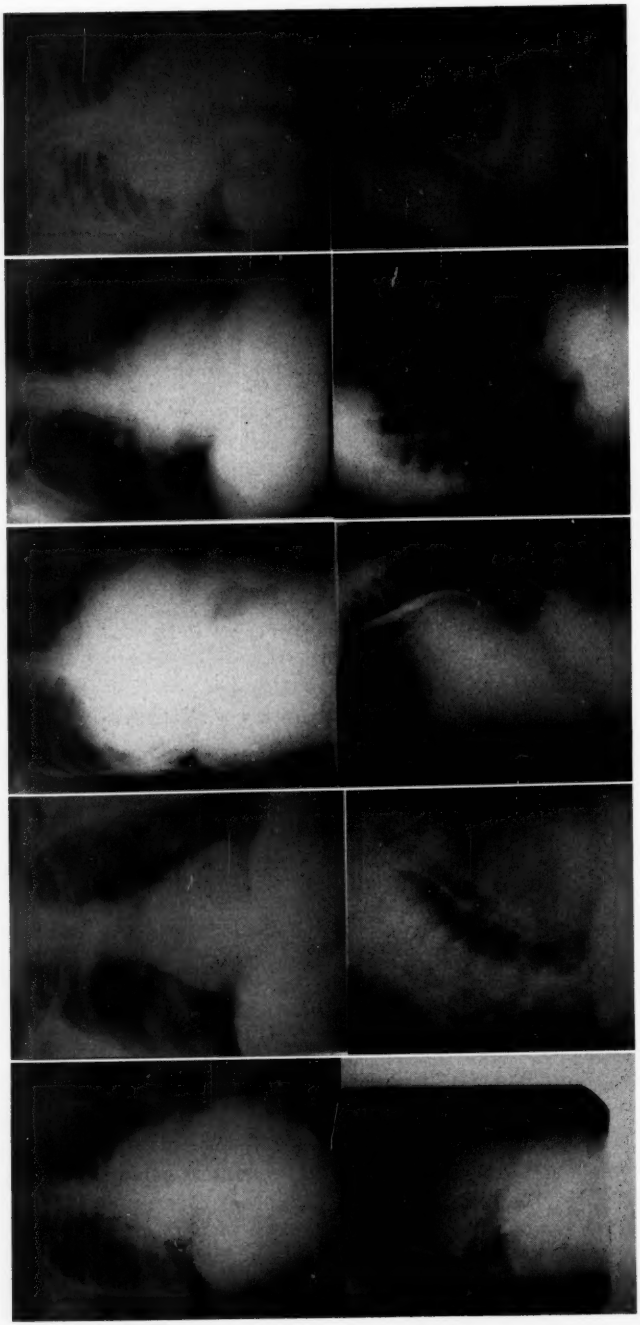


Fig. 12.—The preoperative frontal and lateral roentgenograms of the 5 patients undergoing correction of mitral regurgitation. (Cases 1-5 are arranged left to right.) The advanced states of cardiac disability are evident. There has been no operative or late mortality.

studies on autopsy specimens. Therefore various sized, compressed, polyvinyl sponge cylinders had been prepared in readiness for insertion as described below (Case 5 and Fig. 11).

Preparation and insertion of polyvinyl cylinders for mitral leaflet replacement: Earlier experimental studies[21] indicated that Ivalon cylinders, compressed 2 to 1 or more, changed very little in size over time after being inserted into the dog heart. Moreover, this material prepared in this fashion was well tolerated in the left side of the heart without creating emboli. These compressed Ivalon surfaces became completely covered by a smooth layer of fibrin in 6 weeks.

Cylindrical metal molds of several diameters, ranging from 1.2 cm. (½ inch) to 1.9 cm. (¾ inch), were fabricated and an assortment of polyvinyl cylinders were prepared at 3 to 1 and 4 to 1 compressions. They are sterilized by boiling the mold and the contained sponge for 30 minutes just before use.

In Case 5, a cylinder, 4 cm. in length and 15 mm. in diameter, compressed 4 to 1 was used. Four No. 2 silk stitches attached to a double-armed swedged-on needle were each passed through the cylinder near but slightly to one side of its equator as shown in Fig. 11, *b*.

Then, with care to keep these preplaced stitches oriented, the needles were passed from below upward coming directly through the annulus of the contracted and scarred mural leaflet. The opposite needle of each stitch was then placed similarly from below upward, 3 to 4 mm. medial (toward the free edge of the mural leaflet) as a vertical mattress stitch as portrayed (Fig. 11, *c*). Then, each stitch was tied over a narrow strip of compressed Ivalon.

This cylindrical prosthesis replaced the lost substance normally provided by the mural (posterior) mitral leaflet and became a firm buttress against which the aortic (anterior) mitral leaflet closed (Fig. 11, *d*). A gratifying feature observed in the previously mentioned animal studies was the absence of any tendency for the free leaflet to form adhesions to this Ivalon cylinder (see Fig. 1, reference No. 21).

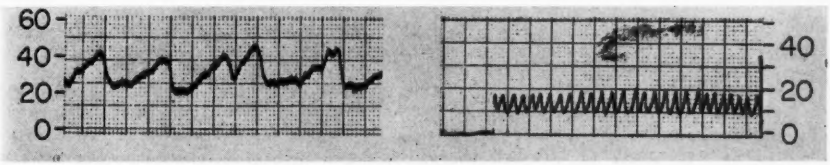
Report of Cases.—

During the past 14 months at the University of Minnesota Hospitals, 5 patients, all far advanced in their clinical stage of the disease, have undergone direct vision reconstruction of the mitral valve for pure mitral insufficiency.[35-37] In 4 of these patients, we have been favorably surprised to find valve leaflets that were remarkably good, in fact they were virtually normal in their consistency. The regurgitant flow seemed to be due primarily to dilation of the annulus fibrosus about the mitral valve. In these patients, surgical repair was made by annuloplasty. In the fifth patient the annulus was of normal circumference, and the regurgitation was due to a severe loss of substance involving the entire mural (posterior) leaflet of the mitral valve. Repair in this patient consisted of insertion of a prosthesis of compressed polyvinyl plastic sponge (Ivalon) together with one annuloplasty stitch. Details concerning these 5 patients are presented below and summarized in Table III. The preoperative chest roentgenograms for these patients are reproduced in Fig. 12.

TABLE III. SURGICAL REPAIR OF PURE MITRAL INSUFFICIENCY UNDER DIRECT VISION UTILIZING THE PUMP-OXYGENATOR

CASE AND AGE	WEIGHT (KG.)	ETIOLOGY OF LESION	CORRECTIVE PROCEDURE	LEFT ATRIAL PRESSURES (MM. Hg)		DURATION OF BYPASS	FLOW RATE (C.C./ MIN.)	PLASMA HEMO-GLOB. (MG. %)	ARTERIAL pH		CLINICAL IMPROVE-MENT
				PREOP.	POSTOP.				PREOP.	POSTOP.	
Case 1 D. D., 15	28	Fibroelas-tosis?	Annuloplasty	43/26	18/10	23′ 35″	1,200	15	7.62	7.63	Good
Case 2 W. D., 43	75	Rheumatic	Annuloplasty	48/20	30/20	25′ 38″	2,600	62	7.50	7.49	Excellent
Case 3 N. B., 19	45	Rheumatic	Annuloplasty	30/15	20/12	28′ 50″	2,300	61	7.44	7.51	Excellent
Case 4 W. O., 39	56	Rheumatic	Annuloplasty	50/20	17/5	22′ 22″	3,000	59	7.41	7.43	Excellent
Case 5 R. G., 43	59	Rheumatic	Insertion of valvular prosthesis together with annuloplasty	—	—	35′ 21″	3 500	50	7.43	7.39	Excellent

CASE 1.—D. D., a boy of 15, had had a murmur detected at 9 months of age. When he was 11 years old, a coarctation of the aorta had been resected, and the presence of mitral insufficiency was confirmed by exploratory cardiotomy. At 12, he developed irreversible atrial fibrillation and progressive cardiac deterioration. At the time of surgery on Aug. 29, 1956, he was in American Heart Class IV E, being confined to bed with intractable right and left heart decompensation. Despite digitalization to the toxic level and complete bed rest, a persistent tachycardia was present. He was considered terminal by his cardiologist,* parents, and ourselves. He had a Grade 4 systolic murmur and thrill at the apex. At operation both mitral valve leaflets were slightly thickened but otherwise appeared virtually normal both as to consistency and leaflet area. The annulus was greatly dilated and the valve function revealed marked regurgitation due to this. Operative repair consisted of placing five No. 2 silk mattress sutures in the posterior aspect of the annulus and tying them down over pillows of compressed Ivalon sponge. This suturing completely obliterated the regurgitant jet, and there was no thrill in the atrium at completion of the perfusion run. The left atrial pressure was reduced from 43/26 before to 18/10 mm. Hg after the reparative procedure (Fig. 13). In the immediate postoperative period his improvement was rapid. A most gratifying objective response was a 12-pound weight loss during this interval from diuresis of the chronic edema fluid in his tissues. Fourteen months after the operation he is doing well and has been able to return to school. Digitalis is still required to control the atrial rate but this remains at 75 to 90 when he is ambulatory. The etiology of the mitral insufficiency in this patient remains uncertain although endocardial fibroelastosis has been suspected.



A. *B.*

Fig. 13.—Mitral regurgitation, left atrial pressures (D. D., aged 15 years). The correction of valvular incompetence as manifested by the immediate reduction in left atrial pressures in our first patient undergoing annuloplasty in 1956 (Case 1, Table III).
A, Before correction, 42/22 mm. Hg. *B*, After correction, 18/10 mm. Hg.

CASE 2.—W. D., a 43-year-old man, had had no history of rheumatic disease, but atrial fibrillation was noted on the electrocariogram in 1948. Since then he had experienced progressive cardiac failure, poorly controlled by digitoxin. He had a laparotomy for mesenteric embolus in 1953. A cerebral embolism 6 months before this present admission resulted in a left hemiparesis from which he was gradually recovering. At the time of this operation on his mitral valve, Dec. 28, 1956, he was in American Heart Class IV D and had Grade 3 systolic and diastolic murmurs at the apex. At operation the mitral valve was heavily calcified anteriorly. Stenosis was present by valve fusion at the anterior commissure. A very large regurgitant jet existed posteriorly. The anterior commissure was incised for 3 cm. and two No. 2 silk mattress stitches were tied over Ivalon to delimit the posterior extent of the annulus. No atrial or ventricular thrill could be felt after completing the perfusion. The atrial pressure was reduced from 48/20 to 30/20 mm. Hg after the annuloplasty. The patient, who had not worked during the 7 years before surgery, now has returned to a full-time position as an x-ray technician.

CASE 3.—N. B., a 19-year-old girl, had had rheumatic fever at 14 years of age followed by repeated hospitalizations for episodes of heart failure. Despite digitalis therapy and rigid salt restriction this young woman had chronic heart failure leading to jaundice from cardiac cirrhosis. At the time of surgery she was in American Heart Class IV D with a

*Dr. Herman K. Hellerstein, Cleveland, Ohio, to whom we are indebted for insisting that we operate upon this first patient.

Grade 4 systolic murmur and thrill at the apex. At the operation, the left atrium was fantastically enlarged (Fig. 12) and the mitral annulus was proportionately dilated. On the other hand the leaflets were not calcified but slightly thickened. The most evident locus of insufficiency was posterior but a significant reflux existed at the anterior pole also. An annuloplasty was created by placing No. 2 silk mattress sutures in the posterior aspect of the annulus and one mattress suture anteriorly. After these had been tied down over Ivalon, the valve was much more competent, and the atrial pressure was reduced from 30/15 to 20/12 mm. Hg. Postoperatively, only a soft Grade 1 systolic murmur was present. This follow-up has been short, but the patient is improved dramatically. Her salt restriction has been eliminated and she is on a regular diet now for the first time in years. Digitalis has been continued to control the heart rate. Evaluation of the result in this case is best summarized in her own words, "A New Life."

CASE 4.—W. O., a 39-year-old man, had had rheumatic heart disease at 21 years of age. Heart failure developed one year before this operation. He was well compensated on digitoxin, but he was unable to work as a farmer because of lack of physical stamina. Attacks of paroxysmal nocturnal dyspnea were frequent during the year just prior to this admission. At the time of surgery he was in American Heart Class III D and had a Grade 3 systolic murmur at the apex in addition to a Grade 2 diastolic murmur at the apex and atrial fibrillation. At operation, the mitral valve was widely regurgitant with slight stenosis at the anterior commissure. This stenotic anterior commissure was incised 1 cm. and the regurgitant channel through the posterior commissure was obliterated by two No. 2 silk sutures tied over Ivalon which narrowed the annular ring. The left atrial pressure was reduced from 50/26 to 17/5 mm. Hg and, postoperatively, only by means of phonocardiography was it possibly to detect any systolic murmur. His follow-up has been short too, but the patient is now on a regular diet and not taking digitalis.

CASE 5.—R. G., a 43-year-old woman, had had rheumatic fever at age 12 with the onset of atrial fibrillation at age 23 and then episodes of cardiac decompensation recurrent until the time of this surgery. A therapeutic abortion had been performed when the patient was 25 because of severe decompensation in the fourth month of gestation. Paroxysmal nocturnal dyspnea, ascites, ankle edema, and frequent episodes of acute pulmonary edema were prominent in her history. She had been on digitalis and a low salt diet continuously for 20 years. At the time of her admission she was in American Heart Class III D and had a Grade 3 systolic murmur at the apex. She went into shock as soon as she was anesthetized. Her heart action was very feeble and the systemic arterial blood pressure had dropped to 60 mm. Hg and hovered at this critical level during the chest opening period. In the race to perform the cannulations and put the patient on the pump-oxygenator before cardiac action failed entirely, it was deemed unwise to take time for measuring the left atrial pressures. Once the patient was linked to the pump-oxygenator her status immediately improved, and the operation could thereafter proceed at a more leisurely pace.

Upon opening the left atrium, a slight stenosis at the anterior commissure and severe posterior regurgitation were evident. Since the mural cusp of the mitral valve was virtually absent, a cylinder of compressed Ivalon sponge (4 cm. in length and 15 mm. in diameter) was placed horizontally underneath this structure and sutured in place as described (Fig. 11). One annuloplasty mattress stitch of No. 2 silk tied down over the Ivalon shortened the posterior annular segment. The regurgitant jet was almost completely abolished by these procedures. The patient's heart took over immediately and established a normal blood pressure at the conclusion of the perfusion. Postoperatively only a Grade 1 systolic murmur was audible at the apex. To date, this patient, like the others, has been impressively improved. For the first time in 20 years she is able to eat a regular salt content diet. It is quite obvious to us from her precarious condition just after being anesthetized and during thoracotomy that she could not have survived any operative procedure which did not immediately and substantially improve her mitral function.

Discussion.—

As a group, these patients undergoing correction of mitral insufficiency have been among the sickest patients preoperatively upon whom the authors have undertaken cardiac surgery. Thus, while the series operated upon remains small, the lack of operative or late mortality and the gratifying improvement, self-evident in each instance, clearly indicates the value of the described reparative procedures carried out upon the incompetent mitral valve under direct vision.

As already mentioned in reference to surgery upon the aortic valve, there will likely be encountered occasional patients in whom the valve leaflets have undergone virtually total destruction and complete valve replacement will be the only acceptable surgical treatment. This successful replacement of much of the mural (posterior) mitral leaflet, the one most frequently damaged secondary to valvulitis, represents an important advance in that regard.

As the principles and our knowledge of reconstructive procedures increase, it is evident that this ultimate approach of complete mitral or aortic valve replacement may be necessary much less frequently than we once had thought. From this admittedly limited experience, we now believe that the surgical treatment of the primarily insufficient mitral valve may well become a more truly corrective procedure than that of the blindly performed operation for mitral stenosis because of the much better quality of the leaflet tissue in most patients with the former condition.

MITRAL STENOSIS

The individual with pure mitral stenosis in need of surgical relief has a good chance of being benefited by a carefully performed valvotomy by the indirect or blind techniques classically described by Bailey, Harken, and others. The principle problems remaining in this field for cardiac surgeons are those found in the patients with complicating factors which have been found to increase mortality and morbidity while lessening the palliation achieved. While some surgeons have sought to overcome these problems by describing various technical and instrumental variations, the obvious solution seems to us to be a direct vision approach for these patients.

Present Indications for An Open Operation Utilizing the Pump-Oxygenator for Mitral Stenosis.—

1. The considerably higher operative risk recorded for closed mitral commissurotomy performed in patients with clinically far-advanced states of disability (Class IV).

2. A history of embolization prior to surgery or known or suspected large atrial clots or tumors.

These two indications will also encompass many patients with unsuspected left atrial myxomas.

3. Patients with apparent restenosis after a seemingly adequate valvotomy.

4. Presence of or any suspicion of mitral regurgitation.

TABLE IV. SURGICAL REPAIR OF MITRAL STENOSIS UNDER DIRECT VISION UTILIZING A PUMP-OXYGENATOR

CASE AND AGE (YR.)	SEX	WEIGHT (KG.)	LESION	ETIOLOGY	DATE OF OPERATION	PROCEDURE	DURATION BYPASS (MIN.)	CLINICAL RESULT
Case 1 3	M	13	Mitral stenosis; ventricular septal defect	Congenital	3/29/56	Rt. ventriculotomy; closure V.S.D.; left atriotomy; mitral valvotomy	38	Excellent
Case 2 52	F	40	Mitral stenosis; aortic regurg. and stenosis	Rheumatic	5/23/56	L. atriotomy; mitral valvotomy; aortotomy; aortic valvuloplasty*	18	Excellent
Case 3 3	M	9	Mitral stenosis; ventricular septal defect	Congenital	6/4/56	Rt. ventriculotomy; closure V.S.D.; left atriotomy; mitral valvotomy	14	Excellent
Case 4 41	F	56	Mitral stenosis†	Rheumatic	1/16/57	Left atriotomy; mitral valvotomy	19	Good
Case 5 13	F	34	Mitral stenosis;‡ aortic regurg.; tricuspid regurg.	Rheumatic	2/27/57	Left atriotomy; mitral valvotomy	29	Died

*Retroperfusion of coronary sinus for 13 minutes. (This is same patient as Case 3, Table I.)
†Mitral regurgitation was suspected preoperatively, but only pure stenosis was found at operation.
‡Had previous mitral valvotomy with no improvement.

5. Patients with multivalvular disease or other intracardiac lesions requiring an open procedure.

Direct vision surgery upon the mitral valve has been a very satisfactory procedure and there is little doubt that the indications for an open procedure are likely to be progressively widened in the future as experience with this procedure grows in various centers.

Surgical Technique for Open Mitral Valvotomy.—

The thoracotomy incision is the same as that already described for mitral regurgitation and aortic valve disease; namely, a right posterolateral thoracotomy. This same incision, of course, provides excellent exposure to the tricuspid valve should significant disease be found there. The left atriotomy has been performed anterior to the insertion of the pulmonary veins.

Rather unexpectedly one of the unanticipated problems of direct vision surgery for mitral stenosis has been the finding that in the congenital lesions as well as in some of the acquired stenoses of the mitral valve the line of fusion of the leaflets may be so perfect that no visual trace of the commissures remains. In such cases the line of attachment of the chordae tendineae has proved to be a valuable guide and landmark for making the proper division. Usually we have utilized the ordinary surgical scissors and scalpel for these direct vision commissurotomies. The valve leaflets, chordae tendineae, and papillary muscles are carefully inspected visually. Then a finger is inserted underneath the leaflets between the chordae tendineae of the respective leaflets and if the line of fusion of the leaflets is not apparent the incision is made upon the finger.

Results.—

Five patients have had direct vision mitral commissurotomies for mitral stenosis through a left atriotomy incision during total cardiopulmonary bypass utilizing the pump-oxygenator. We have had one operative death, no late deaths, and in the other 4 the results have been successful. All 5 of these patients had other complicating lesions as indicated above as a basis for their selection.

Relevant data upon these patients are listed in Table IV.

In both of the patients with congenital mitral stenosis associated with a congenital ventricular septal defect we have been alerted by our pediatric cardiologists* to the possibility of a coexisting mitral stenosis because of certain unusual features in their work-up. These were varying combinations of: an unusually loud diastolic murmur of mitral quality heard best at the apex, unusually marked left atrial enlargement noted at cardiac fluoroscopy, notching of the P waves in the electrocardiogram and greater than anticipated pulmonary wedge pressures measured at cardiac catheterization. None of these findings is diagnostic in itself, but are sufficient to arouse a suspicion of this associated defect. At surgery both patients had prominent diastolic thrills present in the left ventricle. In these patients we opened the right ventricle

*Drs. Ray Anderson and Paul Adams.

and repaired the ventricular septal defect first and then restored the circulation. The left ventricular diastolic thrill persisted in both and so the pump-oxygenator was turned on again and the left atrium opened for the repair. This sequence rules out the possibility of opening the left atrium needlessly for a relative mitral stenosis which can occasionally occur in a patient with an unusually large pulmonary blood flow.

The one death was in a 13-year-old girl with a definite history of rheumatic fever beginning at the age of 5 years. In March of 1956, during a classic mitral commissurotomy at another medical center, the heart arrested and after some difficulties the beat was restored. Convalescence was incomplete and chronic right and left decompensation persisted despite limiting her activity, hospitalization, and the other usual medical methods. Right heart catheterization disclosed severe pulmonary hypertension (85/35 mm. Hg) and no shunt. Left heart catheterization disclosed a left atrial-left ventricular diastolic gradient of 26 mm. Hg with no evidence of mitral incompetence but with the typical findings and murmur of aortic insufficiency. She also had tricuspid regurgitation. At operation, the mitral valve was severely stenotic and calcified and although both commissures were readily opened to the annulus relatively little flexibility of the leaflets remained. Intermittent aortic occlusion was necessary to control blood loss from the aorta during the left atriotomy. No attempt was made to attack the tricuspid or aortic regurgitation. Although the operative procedure was uneventful and her immediate postoperative status seemed good, cardiac arrest occurred without warning later on the day of operation. In such a patient now we would advocate the surgical treatment of the other valvular lesions at the same time.

SUMMARY AND CONCLUSIONS

1. Direct vision reparative procedures making use of total cardiopulmonary bypass with a pump-oxygenator have been described for aortic stenosis, aortic regurgitation, mitral stenosis, and mitral regurgitation.

2. New operative techniques, made possible by the increased accuracy and scope afforded to the surgeon by direct vision, have been devised for the correction of aortic regurgitation and mitral regurgitation. The results have been particularly successful for those patients afflicted with mitral regurgitation.

3. Currently all patients with aortic stenosis, aortic regurgitation, or mitral regurgitation and in need of surgical treatment are best managed by an open bypass operation. Patients with pure mitral stenosis and free of complicating factors which are known to increase morbidity and mortality are treated by the closed mitral valvotomy. The indications for an open operation for mitral stenosis are the presence of one or more of these above-mentioned additional complicating factors. For the future, it is likely that these indications for a direct vision procedure for mitral stenosis will be progressively broadened.

4. The unilateral right posterolateral thoracotomy through the bed of the fourth or fifth rib offers excellent access to the aortic or mitral valve areas

and the good exposure afforded by use of this incision has been an important factor in the successes obtained. Occasional patients with other congenital lesions in the left chest may require a bilateral anterior thoracotomy.

5. Retrograde perfusion of the coronary sinus in combination with a pump-oxygenator has been used in 8 patients for a direct vision aortic valvuloplasty.

6. Five of the 8 patients with aortic valvular disease survived the operative procedure and attained excellent clinical improvement following direct vision valvuloplasty. Two of the 3 deaths occurred in infants. The other failure was due to the production of aortic insufficiency in a patient with a severe distortion and calcification of the valve due to acquired disease. Now, we believe that it is better for patients with such rigid and distorted valves to relieve stenosis by creation of a bicuspid aperture. In the other acquired lesions with less advanced destruction and a greater degree of flexibility remaining, restoration of the triangular orifice still is sought for.

7. In all of these operations the retroperfusion of the coronary sinus appeared to protect the myocardium well against anoxia. There were no instances of cardiac arrhythmia even though a significant percentage of the patients had far advanced left ventricular disease.

8. Acetylcholine has also been used in combination with the retroperfusion in 2 patients. It was injected into the retrograde catheter and provided a dry still field while the aortic valvuloplasty was being performed. Both patients had an excellent clinical result.

9. Total cardiac ischemia of brief duration resulted in extensive myocardial necrosis in a patient with acquired aortic stenosis, and this approach is not recommended for aortic valve surgery.

10. Evidence is advanced to support the belief that total cardiac ischemia, even with the additional protection offered by potassium citrate asystole, is also a dangerous practice in hearts afflicted with the advanced states of aortic valve disease due to an inability to restore a left ventricular beat in both of the only 2 patients in which it was utilized.

11. Acetylcholine asystole with total cardiopulmonary bypass has been utilized in 6 patients with aortic valvular disease, and has proved of value when the arrest interval was brief. However, a significantly greater incidence of arrhythmias occurred than when retroperfusion was utilized. One operative death in this group occurred in a patient with acquired disease in whom a more prolonged procedure was required.

12. Current practice has been to use the acetylcholine arrest in patients with congenital lesions where the operative repairs require less time and the myocardiums generally have a greater reserve. Retrograde perfusion of the coronary sinus, together with retrograde acetylcholine cardioplegia if needed to facilitate exposure, is the recommended procedure for all patients with advanced degrees of acquired aortic valvular disease.

13. Although acetylcholine cardioplegia (without retroperfusion) appears to be the simpler technique for aortic valve exposure, retrograde perfusion is

undoubtedly the safer method when there is marked myocardial hypertrophy and a longer period is contemplated for the valvulopiasty.

14. The concept of correcting visually either surgically created or primary aortic regurgitation by converting the valve leaflets (by suture) to a bicuspid orifice and prosthetic replacement to make up for any shrinkage or loss of tissue substance is offered. Utilizing this method, the first patient to have a successful complete correction of primary aortic insufficiency is reported.

15. Two new operative techniques have been described for the correction of mitral insufficiency without the production of any stenosis. One procedure, termed annuloplasty, consists in part of selective suturing of the annulus fibrosus under direct vision to reduce its circumference commensurate with the area of valvular tissue present. The other procedure for use in patients with substantial loss of leaflet substance is the insertion of a prosthesis.

Five patients have been treated by these techniques to date. Before surgery all had been seriously incapacitated by severe mitral regurgitation. There has been no operative or late mortality. All are alive and significantly, even dramatically, improved. Moreover, the first patient, whose progress has been followed for more than a year, has not only sustained his initial gains but has continued to improve. Thus, although the series is small, the results indicate that surgical correction of mitral insufficiency is feasible, effective, and lifesaving.

16. Five patients with pure mitral stenosis of acquired or congenital etiology together with other complicating factors or lesions have been treated by a direct vision approach. There was one operative death in this group. The 4 survivors have been benefited significantly.

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Discussion

(Papers by Swan [page 139], Lillehei [page 154] and their associates)

DR. PAUL W. HERRON, Seattle, Wash.—At the University of Washington to date we have operated on 5 patients with mitral lesions using the pump-oxygenator. Three of these had pure mitral insufficiency and all survived the immediate procedure. Two of them had very excellent results. I would like to show two slides.

(slide) This shows the left atrial pressure taken before and after repair of the insufficient valve, and shows a marked reduction in left atrial pressure after correction.

(slide) This is a chest film taken before and 2 weeks after surgery. The change in heart size is apparent.

(movie) I would like to show an excerpt of a movie taken during repair on one of these patients which indicates a possible new approach to the left atrium. It utilizes a right thoracotomy, as advocated by Dr. Bailey, but approaches the left atrium posterior to the pulmonary hilum rather than anterior. We feel this approach may make the mitral valve even more accessible than Dr. Bailey's approach. As yet we have not used this method but will at the next opportunity. We offer this approach for your consideration.

DR. GEORGE H. A. CLOWES, Cleveland, Ohio.—I agree perfectly with the authors that the way to approach this problem is to do it by open surgery. My associate, Dr. Neville, and I have operated upon 2 adult patients with mitral regurgitation using the membrane oxygenator. In both instances, perfusion was quite successful. The first patient has made a very satisfactory recovery. We opened the left auricle and by dividing the commissures and four chordae tendineae under direct vision we got the result we wanted without putting any stitches into the valve itself.

The next case—and I think this is more important—was a failure. The perfusion went perfectly well, the patient made a reasonably good recovery, but died very suddenly with acute pulmonary edema the night after the operation. This patient had been previously operated on and a commissurotomy was done. She had had two diagonal cuts into the major leaflet in the wrong place that had allowed the major leaflet to flap and had created a regurgitation. We had located these things under direct vision, at operation put the commissures in the proper place and then put a stitch into each of the two cuts. When we left the operating room, there was no regurgitation and we thought we had an excellent result. I regret to say that the next morning at autopsy, one of the stitches had cut out and she had a wide-open regurgitation again. It appears that mitral valve lesions will not hold stitches under these circumstances.

The other thing is with regard to Dr. Lillehei's remarks on the necessity for perfusion of the heart during the period of occlusion when one has the aorta open. In a series of dogs some years ago which was reported at a Forum in Atlantic City, we never failed to defibrillate and get a recovery in any period under 20 minutes when the animal was not having the coronaries perfused. On the other hand, if we went along for 30 minutes without any circulation in the heart, the great majority of these animals died of cardiac failure later if they could be defibrillated at all.

DR. DENTON A. COOLEY, Houston, Texas.—The presentation by Dr. Lillehei is most impressive and deserves high praise from all of us. At Baylor University we have used

cardiopulmonary bypass in 155 patients with a variety of cardiac and aortic lesions, and I am convinced that this method offers optimum conditions for open cardiac procedures. At present, I am not convinced, however, that retrograde coronary perfusion is necessary in exposure of the aortic valve for operation. We have operated upon patients with aorticopulmonary septal defects, with aneurysms of the ascending aorta, as well as 9 with aortic stenosis, without retrograde coronary perfusion and have noted no ill effects. On the other hand, in the first patient with calcific aortic stenosis in whom retrograde perfusion was used, ventricular fibrillation occurred immediately after starting the perfusion and cardiac resuscitation was unsuccessful. I believe that exposure of the aortic valve through an ascending aortotomy can be achieved safely without coronary sinus perfusion and valvulotomy accomplished within 5 minutes. For this period of time, the ventricular myocardium will usually continue to contract regularly with a sinus rhythm. After operation we have detected no evidence of myocardial damage caused by this brief period of ischemia. I shall be interested to compare our results with Dr. Lillehei's after we have both had more experience.

DR. CHAS. P. BAILEY, Philadelphia, Pa.—[The corrected discussion by Dr. Bailey has not been returned by the discusser.—EDITOR.]

DR. C. WALTON LILLEHEI, Minneapolis, Minn.—In regard to Dr. Herron's suggestion of entering the left atrium behind the right pulmonary hilus I believe it is relatively unimportant whether the surgeon chooses to make his atriotomy incision there or anterior to the hilus. The mitral valve exposure is excellent by either route. The technical consideration that has seemed important to success has been the choice of the right posterolateral thoracotomy incision to approach the left atrium.

With regard to Dr. Cooley's and Dr. Clowes's comments about stitches in the mitral valve, I emphasized that the annuloplasty stitches are not placed in the valve leaflet tissue at all, and should not be in my opinion, but rather are placed in the annulus fibrosus of this valve from above through the left atriotomy approach.

Another point that I sought to emphasize was the fact that there is a remarkable difference in the tolerance to elective arrest techniques especially those involving the profound relaxation induced by potassium citrate between the human heart with advanced degrees of aortic valve disease when compared to hearts from patients with many types of congenital defects. Suffice it to say that these hearts with massive left ventricular hypertrophy, often with superimposed scattered areas of fibrosis as well, due to actual or relative coronary insufficiency tolerate potassium asystole or any form of even brief hypoxia rather poorly. Certain reasons for this observation have been suggested in the body of our paper. Moreover, as our experience has increased, it has become increasingly evident that, save for exceptional cases of the congenital variety, it is not possible nor advisable to complete an adequate aortic valuloplasty within a few minutes.

The surgical correction of pure mitral insufficiency carried out under direct vision has proved to be a very satisfactory surgical procedure even in some very far advanced patients, approaching or actually in the terminal phases of their disease. The reasons for this are both anatomic (the frequent finding of valve leaflet tissue which is still soft and pliable even though inadequate in quantity) and physiologic (the fact that the hearts are immediately and significantly improved the moment this large leak is corrected which makes the procedure akin to closing an atrial septal defect or dividing a patent ductus arteriosus with a large shunt).

THE SURGICAL CORRECTION OF AORTIC INSUFFICIENCY BY CIRCUMCLUSION

WARREN J. TAYLOR, M.D. (BY INVITATION), WENDELL B. THROWER, M.D. (BY INVITATION), HARRISON BLACK, M.D., AND DWIGHT E. HARKEN, M.D.
BOSTON, MASS.

THE surgical treatment of aortic insufficiency has been disappointing. This discussion touches upon the natural evolution of aortic insufficiency, outlines a morphologic classification, discusses hemodynamic alterations, and reviews the surgical maneuvers evolved to date. A new operation for selected types of aortic insufficiency is presented.

NATURAL HISTORY OF THE DISEASE

Individuals with either rheumatic or syphilitic aortic insufficiency may remain asymptomatic for many years without treatment even while the left ventricle is enlarging. Many observers have emphasized that once symptoms appear, patients with aortic valvular disease deteriorate rapidly. The urgency of this axiom seems difficult to appreciate when dealing with the specific patient.

Segal, Harvey, and Hufnagel[21] have pointed out that aortic insufficiency predominates in males over females by three to one. In their experience, rheumatic origin has been more common than syphilitic. The interval between the onset of recognizable auscultatory rheumatic aortic insufficiency and the development of limiting symptoms may be as much as 10 years. The *initial* congestive failure is an ominous warning but generally responds to appropriate medical therapy. When angina pectoris appears it often heralds the terminal phase of the disease. Bland and Wheeler[3] have also documented the grave prognosis associated with this symptom, particularly at rest. Orthopnea, paroxysmal nocturnal dyspnea, and peripheral edema are late in the natural history of this disease and therefore of limited value in selecting the time for surgery. By contrast Bergeron, Ellis and co-workers[2] have found angina and syncope to be of lesser significance in aortic stenosis.

Syphilitic aortitis and associated insufficiency produce a clinical course comparable to rheumatic regurgitation, but the disintegration is much more rapid.[21] The study of Montgomery, Anderson, and Boone[17] indicates that the average survival time after the appearance of the murmur of aortic insufficiency due to syphilis is approximately 24 months. Aortic insufficiency with congestive failure or angina due to syphilis comes later in life than in rheumatic disease. If bacterial endocarditis is superimposed, the deterioration of the patient may be accelerated.

From the Department of Surgery of the Harvard Medical School at the Peter Bent Brigham Hospital and The Thoracic Service of the Mount Auburn Hospital.

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Read at the Thirty-seventh Annual Meeting of The American Association for Thoracic Surgery at Chicago, Ill., May 4-7, 1957.

DIAGNOSIS

Free aortic insufficiency of the type recognized by water hammer (Corrigan) pulse, diastolic murmur, and left ventricular dilatation is not commonly encountered as a pure lesion. More often there is an associated element of stenosis.

Gorlin and Case[8] have discussed the differentiation of stenosis from insufficiency. Throbbing, even pain over large arteries suggests insufficiency. Sweating, flushing, and episodes of tachycardia, as originally described by Lewis,[15] are more commonly associated with dominant aortic regurgitation. Sweating and flushing are due to peripheral vascular dilatation. Angina, syncope, dyspnea, and orthopnea appear late and are also characteristic of stenosis, so are not helpful in differentiation. DeMusset's sign (bobbing of the head) is usually associated with *severe* aortic insufficiency.

Certain aspects of the physical examination are helpful. Cardiac size, particularly early in the disease before the onset of failure, is often a clue to the dominant pathology. There is early enlargement of the left ventricle in aortic insufficiency. A comparable degree of enlargement appears late in aortic stenosis, and then with frank failure. Regurgitation produces increased activity of the apical impulse. Ancillary signs include bisferious (twin-peaked) carotid pulse, Duroziez's sign, and capillary pulsations.

One of the most important differential observations may be made at fluoroscopy. In the left anterior oblique position, a rocking motion of the left ventricle and aortic arch is seen. This is due to the very large stroke output in systole and reflux in diastole. The extraordinary activity of the aortic arch described as "run off" is due not only to regurgitation but to accelerated forward flow into dilated peripheral vessels.

Aortic murmurs are notoriously misleading. Insufficiency without an accompanying diastolic murmur must be rare. Frequently there is an accompanying "diamond-shaped" aortic systolic murmur transmitted upward to the neck and downward to the apex. The intensity of the murmurs does not quantitate the obstruction or reflux. A systolic murmur, due to turbulence over roughened cusps, may exist without organic stenosis, particularly in the presence of the increased stroke volume. Late in the course of the disease, murmur intensity may decrease due to myocardial failure rather than to any alteration in the valve. The Graham Steell murmur of pulmonic insufficiency may be readily differentiated if the other criteria of significant aortic insufficiency are sought.

Usually there is a wide pulse pressure, but its degree is not helpful in assessing the hemodynamic problem. Gorlin and Goodale[9] point out that the pulse pressure narrows as the systolic level falls and diastolic pressure rises "as the vasodilatation of insufficiency gives way to the low cardiac output and vasoconstriction of heart failure."

CLINICAL CLASSIFICATION

Although surgical experience with aortic regurgitation has been limited, a clinical classification of the disease is useful in evaluation and communication. The broad outline of the American Heart Association Classification is

basic, but specificity for aortic insufficiency must be added just as in our clinical grouping for patients with mitral stenosis. The following classification is suggested. It will be altered as experience dictates.

Group I: Individuals with the murmur of aortic insufficiency who are asymptomatic and whose hearts are not enlarged more than 15 per cent over the predicted transverse diameter.

Group II: Individuals with the murmur and mild limitation due to dyspnea on exertion whose limitation is static and who do not require medical therapy.

Group III: Individuals who have the murmur of aortic insufficiency and significant symptoms, e.g., sweating, flushing, tachycardia, evidence of congestive failure, with or without angina pectoris. These symptoms are held static only by an adequate medical regimen.

Group IV: Individuals whose symptoms are refractory to a strict cardiac regimen.

Group V: Individuals who have refractory congestive changes in spite of a strict cardiac regimen.

MORPHOLOGIC TYPES

Rheumatic fever, syphilis, and bacterial endocarditis are the most common causes of aortic insufficiency.

Rheumatic incompetence of the aortic valve is conventionally ascribed to shortening of the leaflets. The cusps simply do not occlude the base of the aorta during diastole (Fig. 1). However, to this gross classical concept, the dimension of time must be added. When diseased aortic valves are observed on the MacMillan pulsator,* the leaflets not only fail to approximate due to lack of substance, but they move slowly, so that considerable reflux occurs before this inadequate closure (Fig. 1). These valves may or may not be calcific. In advanced stages, the dilatation or failure of the left ventricle frequently results in relative mitral incompetence with further burden. Insufficiency may be associated with minimal to dominant degrees of stenosis, with or without calcification.

Syphilitic aortitis with associated medial necrosis results in dilatation of the annulus and separation of the cusps at the commissures, rendering the valve incompetent. If the cusps themselves are involved, it is by fibrous thickening and fixation of the margins. There may also be cusp adherence to the walls of the sinuses of Valsalva (Fig. 1). This form is less common since the advent of penicillin.

A third important cause of aortic insufficiency may be from endocarditic cusp erosion (Fig. 1). Bacterial endocarditis is presumed to occur on previously diseased or congenitally abnormal valves (Fig. 1).

Other less common forms of aortic regurgitation include congenital malformations and traumatic rupture of cusps. Glendy and White[6] have stated that antecedent disease predisposes to cusp injury from blunt trauma.

*Dr. Ian MacMillan and Dr. Stanley Sarnoff have kindly made a pulsator available for use at the Peter Bent Brigham Hospital.

HEMODYNAMICS

Left heart catheterization has added a valuable tool to clinical and investigative studies. Determination of the left ventricular pressure and pulse contour compared with brachial artery pressure, in the conscious patient, yields significant data about valvular lesions. The measurement of the aortic valve gradient is supplemented by injection of dye or radioactive material into the left auricle or ventricle. Sampling of brachial arterial blood gives a curve from which an estimate of insufficiency, between the points of injection and sampling, is derived. The regression formulas of Korner and Shillingford[14] have been modified and applied to left heart catheterization by Dexter and associates.[5]

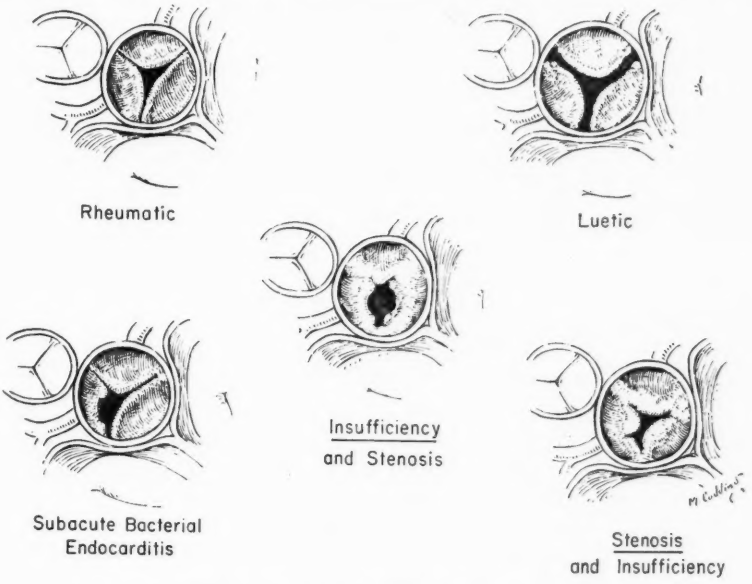

Fig. 1.—Common morphologic patterns of aortic insufficiency.

This has been helpful in differentiating mitral stenosis and insufficiency.[4] It is to be hoped that a comparable degree of proficiency can be developed in the determination of aortic insufficiency. The problem of combined aortic and mitral insufficiency awaits solution.

Peripheral arterial pulse tracings are of little value in differential diagnosis due to the influence of myocardial failure and the degree of peripheral resistance.

PRINCIPLES OF SURGICAL CORRECTION

The burden of aortic insufficiency falls primarily on the left ventricle which may eventually fail. This failure is due to increased work in maintaining forward flow or to inadequate coronary blood flow at a lowered diastolic pressure.

A significant proportion of the added work appears to be relieved by the Hufnagel prosthetic ball valve placed in the descending aorta just beyond the left subclavian artery. Hufnagel and his colleagues[13] feel that this reduction of work may be of the order of 75 per cent. We have had discouraging experience with these valves. Placing the valves is not a problem; however, some patients have continued to have symptoms including increased angina. Sudden death has occurred. The diastolic pressure in the arms can be observed to fall after the insertion of the Hufnagel valve. Mean diastolic pressures have been shown to be lower by Rose, Hufnagel, Freis, Harvey, and Portenopen[19] and also by McKusick, Kahn, Brayshaw, and Humphries.[16] This may have bearing on the increase of angina following valve insertion, and the limited clinical success. It is appropriate to consider more physiologic placement of valves or repairing the incompetence below the level of the coronary ostia.

The same criticism directed at the placement of the Hufnagel valve far distal to the coronary ostia pertains to Murray's[18] use of an homologous aortic valve segment in the same position. The physiologic and hemodynamic disadvantages are compounded by the limitations of homografting itself.

Instead of replacing the valve, Sarnoff and Chase[20] have devised an L-shaped Lucite tube containing a ball valve that affords a new outflow tract at the cardiac apex. This inserts directly into the descending aorta. They have used this extensively in the laboratory. This or some similar principle may be useful at some time in the future.

Upon scrutiny of the morphology of aortic insufficiency and the principles involved in the local correction of regurgitation, at least four additional considerations are warranted.

First.—The first principle concerns incompetence associated with stenosis. At times the incompetence is not due to shortening of the leaflets but to inability of the leaflets to move into the closed position. Often these leaflets are held open in a pyramidal position by fusion at the commissures (Fig. 1). In this situation, fracture of the fused commissures, allowing more *complete* and more *rapid* closure, reduces the insufficiency and corrects the significant stenosis.

Second.—A second principle involves placing an obturator above the existing valve. This obturator, round or spherical in shape, is anchored by flexible moorings to the aortic wall; it moves away from the valve orifice in systole and back to obstruct reflux in diastole. Bailey[1] used such prostheses above combined stenotic and incompetent orifices.

Glenn and his associates[7] have employed a similar principle by placing material through mitral orifices. This substitute for loss of substance in cusp length and occlusive capacity also shortens the closure time of the leaflets. We have placed various substances through the aortic orifice in animals. The most promising would seem to be a braided Teflon cord, approximately 4 mm. in diameter (Fig. 2).

Third.—A third principle involves adding length and flexibility to the existing cusps. This may be accomplished by autografting or suturing material, such as Teflon, to the cusps.

Fourth.—The fourth principle pertains to the reduction of the size of the annulus of the aorta. In such a way, small leaflets may become adequate. Bailey's "sash"[1] employed this principle. This sash was placed so wide of the base of the aorta that it seemed unlikely to be effective. Similarly, commissural suture or neutral cusp plication has been considered. These have not, to our knowledge, had successful human application. Such plication, particularly total neutral cusp infolding, seems unreasonable when one considers the character of ventricular and aortic walls.

Finally, direct uniform reduction of the base at the annulus seems attractive because some pathologic processes producing incompetence are primarily due to dilatation, e.g., syphilitic lesions and diffuse myocardial dilatation. In other instances, the leaflets are shortened and remain flexible. These conditions are partially or completely defeated if there is extensive calcification of the leaflets or the annulus.

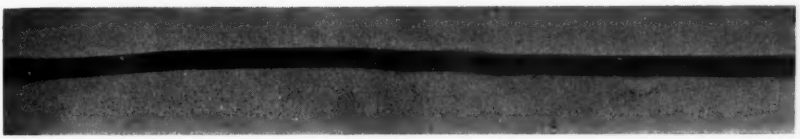

Fig. 2.—Braided Teflon valve seat.

Ideally, circumclusion should be carried out through direct dissection beneath the coronary ostia rather than involving the widespread tissue compression mentioned in connection with the "sash" operation. Proper circumclusion involves placement of this constricting band below the widest girth of the truncated base of the aorta (Fig. 7). This constricting band must be low enough to reduce the area at the very base of the sinuses of Valsalva in order to afford maximum reduction of area to be occluded. The dissection is quite feasible when gently and delicately carried out.

TECHNIQUE FOR CIRCUMCLUSION

The patient is placed in a supine position with the right side elevated to an angle of 35 degrees. A right inframammary incision is made over the fourth interspace and extended transversely across the sternum to the left third interspace (Fig. 3). The right pleural cavity is entered through the fourth interspace. The sternum is transected obliquely connecting the fourth right with the third left interspace. The pericardium is opened obliquely to expose the great vessels and right ventricle. The pulmonary artery and ascending aorta are separated down to and through the conus ligament (Fig. 4). Anteriorly, dissection is carried toward the base of the aorta, reflecting the right ventricular myocardium and pericoronary fat. The right coronary artery is isolated (Fig. 4). The aorta is exposed 1 to 1.5 cm. below the coronary origin. Exposure of the posteromedially placed left coronary artery is more difficult, but it must be adequately visualized in order to place the circumcluding suture. The dissection is carried gently *below the widest diameter of the sinuses of Valsalva,*

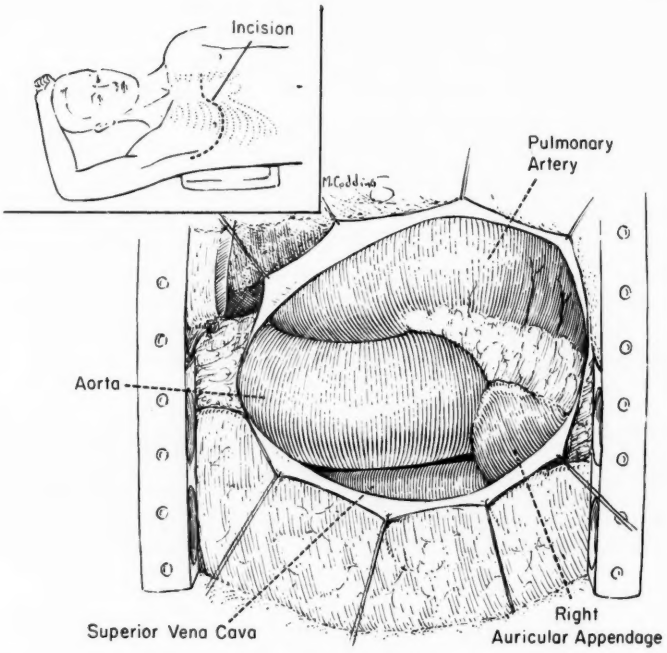

Fig. 3.—Right anterolateral incision and exposure.

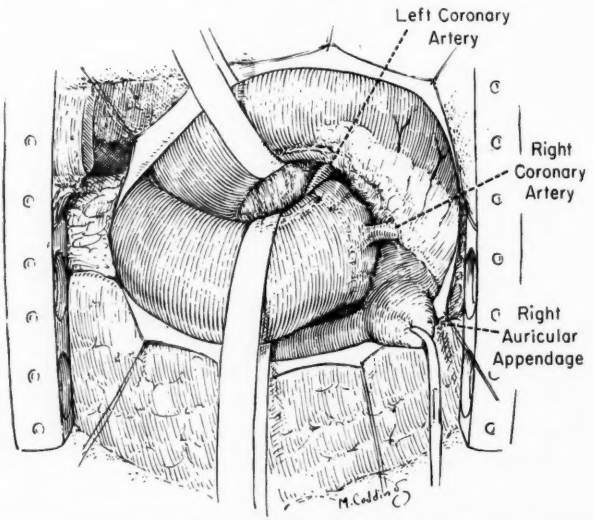

Fig. 4.—Details of coronary artery dissection. Division of conus ligament allows exposure of left coronary artery.

since the circumcluding suture must, on constriction, tend to migrate downward to reduce the aortic valve area, rather than upward and angulate the coronary arteries (Fig. 4). A double-tapered braided silk suture* is used. This suture tapers from No. 3-0 at the swedged malleable vascular needle to No. 5 in the middle and again reduces to No. 3-0 at the other needle (Fig. 5). The circumcluding suture is started lateral to the right coronary artery where a firm anchoring ligature is taken in the myocardium deep in the dissected groove at the base of the aorta. The suture is then passed beneath the right coronary artery (Fig. 6). Another anchoring stitch is placed under the divided conus ligament. The origin of the left coronary artery is underpassed and the left and right fibrous triangles, as described by Barry and Patten,[10] are incorporated in the suture line. The heavier tapered material is advanced so that the base of the aorta is circumscribed by the No. 5 segment. It is emphasized that the suture must be placed well below the origin of the coronary vessels and below the widest girth of the promontories of the sinuses of Valsalva,

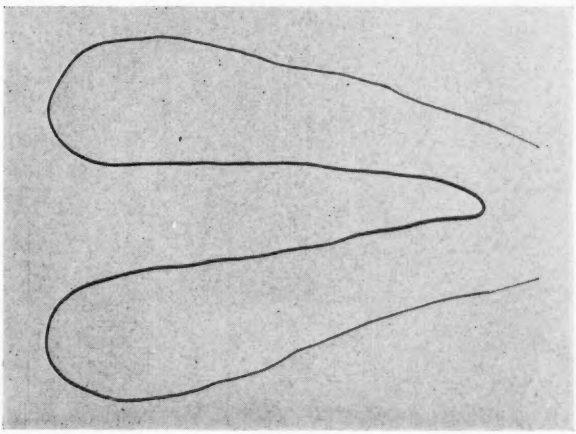

Fig. 5.—Double-tapered suture with malleable swedged vascular needles.

as described previously. In earlier dissection this was not adequately appreciated. Palpation of the base of the aorta by a finger within the right auricle facilitates placement of the stitch low in relation to the neutral (noncoronary) cusp (Fig. 6). This tends to ensure the low position of the circumclusion for more effective coaptation of cusps and protection of coronary arteries. Having thus placed the circumcluding suture (Fig. 7), it may be used alone or entwined with another No. 5 silk suture, or even cotton umbilical tape, to provide added bulk.

The degree of reduction of the aortic base is a delicate determination. As the constriction is increased, the cusps can be felt to close with a sharp impact in diastole. The anesthesiologist may detect an elevation of the diastolic pressure. In only one instance was intra-aortic digital control used as the suture

*Ethicon, Inc., Somerville, New Jersey.

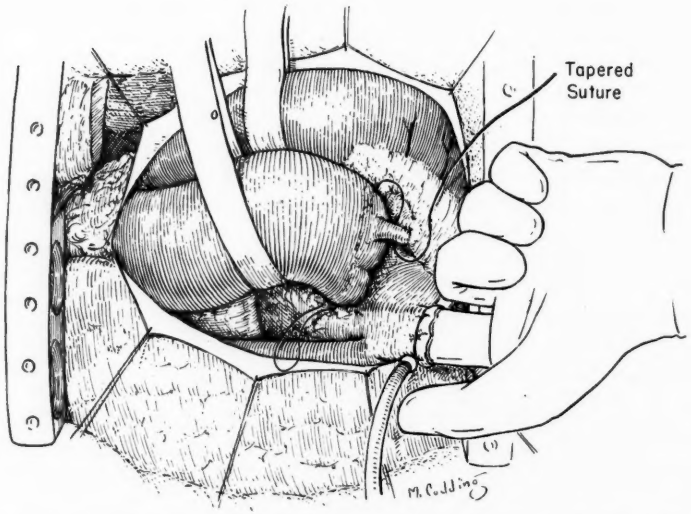

Fig. 6.—Double-tapered suture ligature passed under coronary arteries, anchored low in relation to neutral (noncoronary) cusp. Finger as guide is in right atrium.

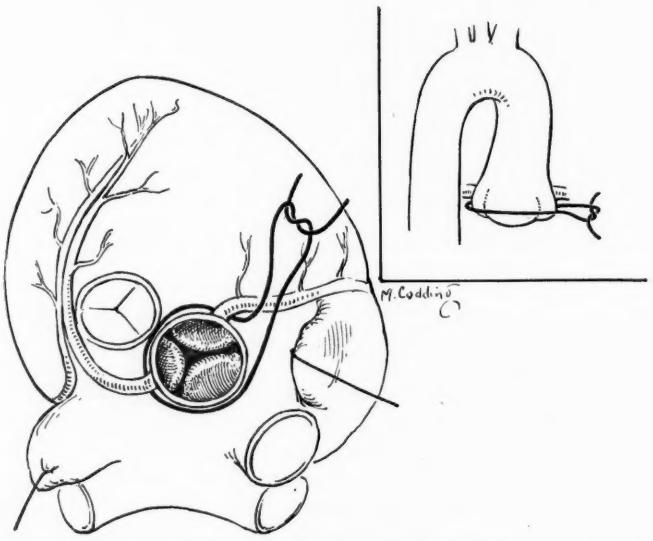

Fig. 7.—Location of circumcluding ligature.

was tied. This was accomplished by suturing an Ivalon operating tunnel to the ascending aorta, through which the surgeon palpated the valve as the tie was made. This seems unnecessarily complicated.

Operative Experience.—Eleven patients with pure aortic insufficiency have had the circumclusion operation. Five are living and improved. There were 4 operative deaths and 2 late deaths. All were males varying in age from 20 to 54 years. The etiologic factor was rheumatic fever in 8, syphilis in 2, and congenital malformation in one. All but one were in congestive failure at the time of operation. Five had angina pectoris and 4 had calcification of the aortic valve. All had systolic as well as aortic diastolic murmurs. Further details are incorporated in Table I.

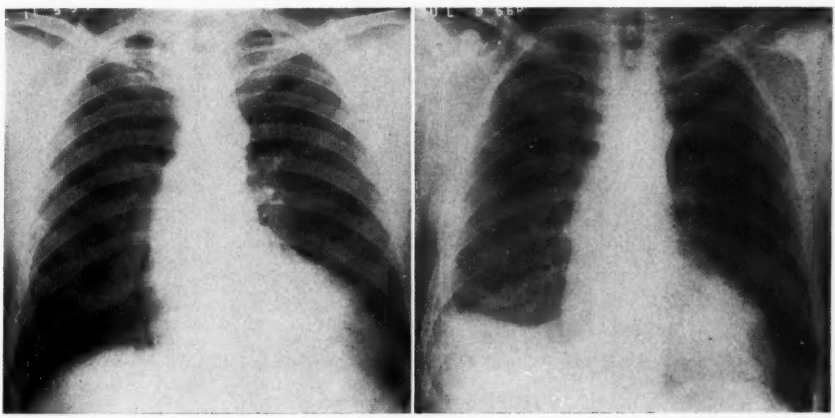

Fig. 8.—Patient A. P. Cardiac silhouette before and one year after circumclusion for aortic insufficiency. *Left*, Before operation, July 11, 1955. *Right*, After operation, July 9, 1956.

DISCUSSION

Objective evaluation of this operation has been difficult. The technique must be modified according to the anatomic findings and cannot be rehearsed on animals. All but one patient operated upon were terminal. Among such a group of patients, a useful procedure can fail to prove itself. Fortunately, the first patient was conspicuously benefited. An orthopneic, dying man in overt congestive failure, with angina and syncope in bed, was out of failure and free of pain and syncope when discharged on the tenth postoperative day. He returned to vigorous farming for one year. Reduction in cardiac size is illustrated (Fig. 8). Eventually, after 18 months, he succumbed to congestive heart failure secondary to a pulmonary infection. The first 12 postoperative months of rehabilitation were gratifying and prompted further trial of the operation.

The second patient had an aorta with a pyramidal base and the dissection was not carried deep enough to prevent upward migration of the constricting ligature. The right coronary artery was compromised and the patient died

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TABLE I. CIRCUMCLUSION FOR AORTIC INSUFFICENCY—OPERATIVE EXPERIENCE

PATIENT	AGE	ETIOLOGY	LEFT VENTR. FAILURE	ANGINA	CALCIFICATION IN VALVE	DATE OF OPERATION	RESULT	REMARKS
1 A. P.	44	Syphilitic	+	+	+	7/27/55	Late death	Marked improvement for one year; transient failure at 12 months, responded to therapy; died 18 months later, congestive heart failure
2 L. R.	20	RHD	+	0	0	10/21/55	Operative death	Died 24 hours postoperatively; autopsy, suture compromised right coronary artery
3 R. G.	39	RHD	+	0	0	3/5/56	Operative death	Hufnagel prosthesis 3 years previously, followed by recurrent failure; died 15 days postoperatively, hepatic failure
4 P. S.	36	Congenital	+	0	0	3/26/56	Late death	Associated coarctation, aortotomy and digital control of circumelusion, wound dehiscence and aortic rupture; died 33 days postoperatively
5 W. P.	41	RHD	+	+	0	6/6/56	Operative death	Sudden death 20 hours postoperatively; suture well placed

PATIENT	AGE	ETIOLOGY	LEFT VENTR. FAILURE	ANGINA	CALCIFICATION IN VALVE	DATE OF OPERATION	RESULT	REMARKS
6 J. S.	44	RHD	+	0	+	8/14/56	Improved	Totally disabled by congestive heart failure preoperatively; postoperatively, working
7 A. K.	39	RHD	+	+	+	9/24/56	Improved	
8 H. P.	39	RHD	+	0	0	10/3/56	Improved	
9 W. G.	44	RHD	+	0	+	11/5/56	Improved	
10 J. G.	29	RHD	0	+	0	12/19/56	Improved	Only patient operated without failure, angina decubitus relieved
11 H. P.	54	Syphilitic	+	+	0	1/4/57	Operative death	Diffuse atelectasis; died 36 hours postoperatively

the day after surgery. This led to a more extensive dissection and the development of the double-tapered suture (Fig. 5), which has considerably improved the security of placement.

The third patient in this series was in cardiac failure and died 15 days after surgery in hepatic coma. He had had a Hufnagel valve placed 3 years previously.

The fourth death occurred 33 days after operation in a patient who had to be readmitted to the hospital because of dehiscence of his wound. The aortotomy also ruptured and the patient exsanguinated. Whether infection or the known liver disease was responsible for this total failure of healing cannot be established. Autopsy indicated that the ligature was well placed and did correct his aortic incompetence. An associated coarctation of the aorta may have been significant.

The fifth death occurred suddenly 20 hours after surgery. It was of the sudden unexpected type seen in patients with severe disease of the aortic valve and was presumed to be from ventricular fibrillation. At autopsy, the circumelusion was perhaps 3 mm. higher than the ideal position and had not been tightened sufficiently but it did not compromise the coronary arteries.

The sixth death was due to massive atelectasis and occurred on the second postoperative day. This patient had been hyperventilated with 100 per cent oxygen because of marked S-T segment depression during operation. Extubation and shift to nasal oxygen without nitrogen transition probably contributed to the atelectasis. The circumelusion appeared effective on direct inspection and when studied on the pulsator.

This high mortality rate seems less formidable when viewed as the result of salvage surgery in a developmental phase. Indeed the first death was 1½ years after surgery and the patient enjoyed total rehabilitation from a moribund preoperative state for a period of more than one year. The surviving patients have shown encouraging improvement.

Efforts are being made to find objective means of evaluating this operation. Cardiac output studies and dye dilution curves may provide objective data. No patient has been permanently relieved of his aortic diastolic murmur, but this is not a reliable criterion of the hemodynamic situation as discussed above. The clinical course and serial roentgenograms seem to constitute our best current means of assessment.

The fear that the circumeluding suture might erode through the base of the aorta seems unwarranted. This does not occur in dogs when the descending aorta is reduced to one half of its lumen with silk, nylon, or cotton material. It had not occurred in any of the patients presented here who died. This includes the patient who survived 18 months.

The dissection of the base of the aorta may at first seem a formidable procedure. A limited amount of practice, however, will convince one that this can be done if reasonable care is employed. The division of the conus ligament to expose the bases of pulmonary artery and aorta and the left coronary artery is a vital maneuver. Better suture material may be developed in the future but a very satisfactory one is available.* A knowledge of this dissection may be useful when valve replacement becomes practical.

*Ethicon, Inc., Somerville, New Jersey.

This technique of circumclusion constitutes a reasonable corrective procedure which should carry an acceptable operative risk for patients not terminally ill with noncalcific or only slightly calcific incompetent aortic valves.

SUMMARY

The clinical course, diagnosis, morphologic types, and hemodynamics of aortic insufficiency are discussed. Principles involved in its surgical correction are reviewed. Eleven patients with pure aortic insufficiency have been operated upon by the circumclusion technique. Five are living and improved. There were 4 operative deaths, and 2 late deaths. All but one were in congestive failure at the time of operation. The etiologic factor was rheumatic fever in 8, syphilis in 2, and congenital malformation in one.

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(For Discussion, see page 230.)

THE CLINICAL AND PHYSIOLOGIC CRITERIA FOR SURGICAL CORRECTION OF MITRAL INSUFFICIENCY

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A CONTINUING study to evolve methods for the proper surgical management of patients with mitral insufficiency has been in progress for 5 years.

Initial experimental work led to the successful clinical application of an effective operative technique for correction of mitral regurgitation 2½ years ago.* This was the first reported case in which correction of regurgitation was objectively documented.[1-5] From that date through March, 1957, 49 consecutive patients with severe degrees of mitral insufficiency have been examined.

In this presentation, preoperative, operative, and postoperative findings, as well as current results of management, are considered in an attempt to derive criteria for the selection of candidates for corrective surgery.

CLINICAL MATERIAL

Of the 49 cases included in this report, 7 were males and 42 were females. The ages were between 7 and 58 years. Forty gave a positive history of rheumatic fever or of definite related manifestations. The onset of clearly progressive symptoms varied from 3 months to 38 years prior to our investigation of the case. Progressive symptoms were present for an average of 7.72 years. Fifteen patients were totally incapacitated by their disease from 6 months to 15 years. All were on a medical program for control of congestive failure. This regime consisted of medication with digitalis preparations, mecurial and oral diuretics, as well as low sodium diets and marked restriction of activity for periods from 2 months to 29 years, averaging 7.8 years.

Twenty-six patients were in a state of decompensation at the time of admission to our hospital service. These proved to be cases of medically intractable congestive failure. Three patients had suffered peripheral embolic episodes.

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Read at the Thirty-seventh Annual Meeting of The American Association for Thoracic Surgery at Chicago, Ill., May 4-7, 1957.

*Jan. 20, 1955.

Symptoms in order of severity and frequency were fatigue, dyspnea, palpitations, orthopnea, cough, edema, abdominal fullness or distention, and precordial pain. Two patients had been subjected to mitral commissurotomy, 1½ and 2 years before. Four had previous exploratory cardiotomy.

A systolic murmur at the apex, transmitted to the left sternal border and to the axilla, Grade 3 to 4 in intensity, was present in all cases. A muffled or absent mitral first sound was noted in 26 cases. The mitral first sound was intensified in 17 cases. A markedly accentuated second pulmonic sound was observed in 29 cases. A systolic murmur transmitted to the neck was detected in 5. One of these was proved to have a moderate degree of aortic stenosis. Another is suspected of having this lesion. An apical diastolic murmur was detected in 28 cases. Ascites and/or hepatomegaly were present in 29 cases. Dependent edema and pulmonary râles were evident in 9.

Routine laboratory work was not remarkable except for an occasional mild anemia. Eight patients may have been in a state of low grade rheumatic activity. However, C-reactive protein, antistreptolysin, and antihyaluronidase titers, as well as erythrocyte sedimentation rates, were not consistent.

Six patients were in normal sinus rhythm. Forty-three were in atrial fibrillation. Of the latter, 8 showed frequent runs of ventricular extrasystoles or bigeminal rhythm. Changes suggestive of digitalis effect, myocardial ischemia, or of pericardial activity were noted in 18. Ventricular rates varied between 50 and 96 beats per minute and averaged 76 beats per minute. Two patients showed evidence of atrioventricular dissociation.

Phonocardiograms routinely showed wide amplitude vibrations throughout systole on the apical tracings. Notable diastolic vibrations were seen in a few.

Radiologic studies included fluoroscopic examination and posteroanterior left lateral and both anterior oblique teleoroentgenograms. The findings can be condensed into three groups, arbitrarily divided according to heart size; there were 14 patients with massive cardiomegaly. The cardiothoracic ratio in this group ranged between 0.703 and 0.875, averaging 0.772. Fourteen patients had marked cardiomegaly with cardiothoracic ratios of 0.602 to 0.683, averaging 0.639. Sixteen patients had moderate cardiomegaly with cardiothoracic ratios of 0.464 to 0.595, averaging 0.518. Roentgenograms of 5 patients were not available for measurement. Four of these were operative deaths and one patient is living.

Right heart catheterization was performed in all but 3 patients and partial or complete data are available (Table I). Left atrial puncture was performed, transbronchially,[6] in 23 cases.

The most obvious clinical differentiation of cases in this series was based on the degrees of incapacitation and response to medical management. On this basis the series is separated into two categories. Twenty-six patients were in medically intractable congestive failure. Many were totally incapacitated. Twenty-three were in chronic congestive failure, but responded to medical management. A few were able to perform light tasks but showed fatigue on more than mild exertion.

TABLE I

CASE	AGE	RA	RV	PA	PVC	LA	LV	ARTERIAL	C.O.	PULMONARY ARTERIOLAR RESISTANCE	TOTAL PULMONARY VASCULAR RESISTANCE
1	28							125/75			
2	24		25/14	80/47	20/11						
3	27		30/ 6	35/ 5	14/11			125/65			
4	41	15/ 7		58/30							
5	19	9/ 2	75/–1	88/35							
6	28	2/–3	20/–5	28/10	16/ 5			125/62			
7	21	1/–3	31/–6	30/11	16/–1			98/57			
8	33	7/ 0		120/60*							
9	38		48/ 0	46/11	49/17						
10	33	10/ 6	80/ 2	76/36	29/15						
11	38										
12	38	3/–2	23/–4	20/ 4				130/60			
13	19	(9)	50/10	55/20	(16)			118/75			
14	29	5/–1	64/ 0								
15	7	3/–4	12/ 1	12/ 5	10/ 6						
16	33	4/–3	42/–3		48/15						
17	25	5/ 0	35/–5	30/ 5	12/ 0			140/80			
18	30	9/ 4	38/ 7	38/18		42/24	130/8	115/65	8.03†		196
19	31	9/ 2	34/ 5			58/25			3.75		348
20	52	10/ 6	35/ 5	35/17				140/48	4.8		384
21	31	14/10	60/ 0	60/20	30/18			120/64			
22	19	-3/–10	35/–7	40/ 6	15/ 6			124/76			
23	34		60/ 0	60/18	40/12	48/†					
24	22	13/ 5	92/ 5	92/44	52/22	60/15		140/84	2.3	975	1998
25	48	24/15	84/10	80/40	52/22	40/17		126/80	1.56	1120	1960
26	35	7/ 2	40/ 3	36/13	32/12	30/17		120/70	2.71	178	766
27	27	(7)	38/ 7	37/18	30/12	42/17		120/60	1.5	624	1338
28	35	5/ 0	45/ 2	45/22	12/ 5	10/ 0		136/68	3.24	160	800
29	18	10/ 6	48/ 8	48/30	35/15	50/10		100/60	2.25	400	1280
30	55	13/10	64/11	64/32	49/20	85/22		116/74	2.05	560	1760
31	17	10/ 3	70/ 6	70/35	22/15	40/24		120/52	3.30	880	1120
32	36	10/ 5	30/ 6	30/13	23/10	23/ 8		108/50	2.80	164	550
33	52	14/10	64/10	64/36	44/22	45/25		155/76	2.67	400	1200
34	47	catheterization contraindicated									
35	31		40/ 5	45/25	28/†	42/25		110/60			
36	29	10/ 5	28/ 7	28/10	23/18	24/12		128/64			
37	36	10/ 3	32/ 6	32/15	30/12			96/48	3.36	89†	500
38	47	8/ 5		30/12	23/9	26/12		120/68	4.44	110	419
39	58		24/ 7	20/10	16/10	35/12		160/88	2.25		490
40	26	15/ 6	45/ 7	45/25	35/16	40/17		100/64	2.6	320	990
41	25	10/ 5	40/ 7	40/22	38/12	44/15		120/70	3.8	212	522
42	32	15/10	42/10	42/20	35/16			118/64	4.86	100	468
43	33	18/ 4	43/12	43/25	42/26	50/22			2.85	351	420
		Patients Who Did Not Have Corrective Surgery									
1	37	20/13	72/16					130/80	2.50		
2	29	3/–4	25/–6	34/–2	14/–2			105/48			
3	54	15/ 7	45/ 9	45/22	30/15	33/15		150/80	5.58	310	492
4	34	8/ 5	50/ 7	50/25	47/14			130/90	2.93	215	880
5	29			40/22	25/10	45/10		140/80	3.71	325	610
6	32	17/12	80/14	80/45	40/25			130/80	2.84	790	1624

RESULTS OF SURGERY

Twenty-five medically intractable patients were subjected to surgery. Definitive surgery could not be performed in 5 of these. Two had such valvular damage that any known operative technique would have been futile. In 3 other patients examination of the size of the cardiac chambers, the degrees of left ventricular dilatation, and their poor tolerance to thoracotomy indicated that they would not be improved by corrective surgery. Three had previous vena cava ligation.[7, 8] In 2 this was done before exploration. One patient was not subjected to further operations. One patient of the intractable group had a vena cava ligation, followed 6 weeks later by corrective surgery and is included below.

Twenty patients in intractable congestive failure were subjected to circumferential suture of the mitral annulus. Three are living. In one, regurgitation was due to rupture of chordae tendineae. This case has been reported elsewhere.[9] The patient is a 55-year-old man who was totally incapacitated but who is essentially asymptomatic 11 months after surgery. It was considered at operation that an excellent mechanical correction of the defect had been obtained. One other patient is now 11 months postoperative. Correction in this instance was less satisfactory. Although he was not expected to survive, he did reasonably well during the first few months postoperatively. No recent follow-up is available. The third living patient had vena cava ligation. She is now 1.5 months postoperative and shows some improvement. Correction of regurgitation in this case was satisfactory.

Seventeen of the patients who manifested intractable failure are dead. Mechanical correction of the regurgitant defect was excellent in 2, good in 5, fair in 2, and unsuccessful in 2. In 5 others, the degree of correction could not be ascertained because of general circulatory deterioration during the operative procedure. Four of these were operative deaths (within one week after operation). One survived 8 months despite 65 minutes of ventricular fibrillation at surgery. This patient is said to have improved slightly at first but subsequently deteriorated. In 10 patients, satisfactory correction of the defect was known to have been obtained at surgery. Three of these were operative deaths. Seven survived one to 8 months postoperatively. One of the survivors was improved physically but mental depression led her to commit suicide 6 months after operation.

Autopsies were performed in 12 of the 17 patients in this group. Eight of these hearts were studied on the pulse-duplicator which demonstrated that 6 were satisfactorily corrected by the purse-string operation. The 2 others possessed the anatomically uncorrectable lesions just mentioned.

To recapitulate then, of 20 intractable cases in which circumferential suture was performed, 3 patients are living. Two of these are 11 months postoperative and one is 1.5 months. Eight survived one to 8 months after surgery and 9 died within the first week. In 16 patients who were operative or late deaths, substantial degrees of correction of the regurgitation were evident from operative observation, autopsy findings, and study on the pulse-duplicator.[10, 11] Indeed, it is possible that the regurgitation was totally eliminated in 3 of these.

This, however, cannot be proved. That correction was lasting was evident in all the late deaths which were autopsied. No corrective effect was observed in 2 and no information is available on one patient.

The causes of death were apparent in only 4 of the fatal cases in which satisfactory correction is known to have been obtained. One patient had ventricular fibrillation during preliminary exploration of the heart. Purse-string operation of the mitral valve was carried out in the presence of this arrhythmia in the hope of improving forward flow. However, all resuscitative measures were of no avail. Two patients had previous exploratory cardiotomy, and dissection through the dense adhesions in the transverse sinus led to uncontrollable hemorrhage when the suture was placed. One patient committed suicide. Three of the remaining 10 patients developed ventricular fibrillation at surgery. One could not be resuscitated, one survived 4 days after 45 minutes of ventricular fibrillation at surgery, one other lived 8 months. No definitive cause of death was noted in these 2 other than progressive circulatory failure. In the 7 other deaths no clear cause of death is known. All of these patients ran a course compatible with progressive heart failure. No significant arrhythmias were detected in this group although 2 patients died suddenly 4 and 5 months after surgery and either ventricular fibrillation or atrioventricular block was suspected. Coronary ischemia could be suspected but this is not clearly indicated by electrocardiograms which reveal mild changes compatible with digitalis effect, traumatic pericarditis, or mild degrees of ischemia. Serial tracings showed improvement with return to the preoperative state within one to 4 weeks postoperatively. Three patients developed a state of peripheral vascular collapse which was gradual in its evolution, intractable, and fatal in 4 to 6 days after surgery. Low grade rheumatic activity preoperatively and/or postoperatively was suspected in 4.

It is our impression that despite satisfactory correction of mitral regurgitation these patients died in a state of forward failure which was rapidly fatal in 3 and led to pulmonary congestion and combined left and right heart failure in 7.

Twenty-three patients were categorized preoperatively in the chronic congestive failure group on the basis of their condition and the response to medical management. Seven of this group are dead. Five were operative deaths, one from an incompatible blood transfusion. One died in ventricular fibrillation at surgery and 3 died 4 days postoperatively in a state of circulatory depression associated with terminal bradycardia in 2. An electrocardiogram was not obtained terminally and although available tracings do not show atrioventricular dissociation, it is strongly suspected that this derangement had occurred. In the third case, irregular ventricular tachycardia was present until death.

Two patients died in the late postoperative period. One died 3 months after surgery from an avoidable technical error which resulted in an infected thrombotic focus on a segment of the suture erroneously placed across the lumen of the left atrium at the atrioventricular ring. This case has been

described previously.[5, 13] Another patient died 8 months postoperatively. Although the cause of death is not clear, the knot of the suture had eroded into the wall of the atrium and presented in the lumen. This may have been a source of emboli not detected at autopsy. This result is also avoidable. Autopsy was performed in all 7 of these patients and satisfactory correction of the regurgitant defect was substantiated.

Sixteen of this group of 23 patients in chronic congestive failure are living 3 months to 2½ years after operation. Mechanical correction of the lesion in these was interpreted as excellent in 4, good in 6, and fair in 6. In the first 4, no regurgitant jet was apparent upon completion of the operation.

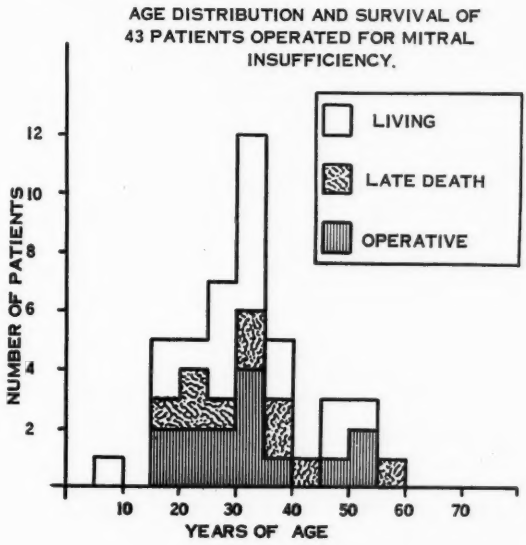
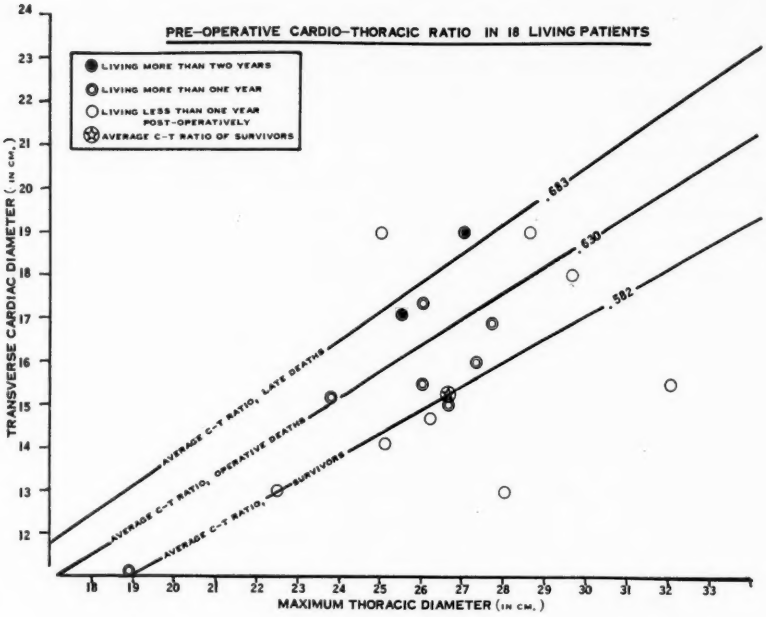


Fig. 1.

The murmur was totally abolished and remained undetectable for up to 2 weeks postoperatively. After this time, a systolic murmur of reduced intensity reappeared in all of these cases. All 16 patients have shown progressive and lasting improvement following surgery. Eleven of these individuals have returned to normal useful activity, either housework or gainful employment in their previous occupations. One of these patients had a preoperative embolic hemiplegia. Four are less than 7 months and one less than 10 months postoperative. This patient had suffered a preoperative peripheral embolus.

The postoperative course in this group has been extremely different from that of patients in the intractable failure group in spite of the fact that 4 of the survivors showed a picture compatible with low grade rheumatic activity pre- or postoperatively.

Seven of the 16 had proved postoperative atrioventricular block within the first 2 weeks following surgery. In 2, digitalis intoxication could have been


PRE-OPERATIVE CARDIO-THORACIC RATIO IN 18 LIVING PATIENTS
LIVING MORE THAN TWO YEARS
LIVING MORE THAN ONE YEAR
LIVING LESS THAN ONE YEAR POST-OPERATIVELY
AVERAGE C-T RATIO OF SURVIVORS
.683
.630
.582
AVERAGE C-T RATIO, LATE DEATHS
AVERAGE C-T RATIO, OPERATIVE DEATHS
AVERAGE C-T RATIO, SURVIVORS
TRANSVERSE CARDIAC DIAMETER (IN CM.)
MAXIMUM THORACIC DIAMETER (IN CM.)

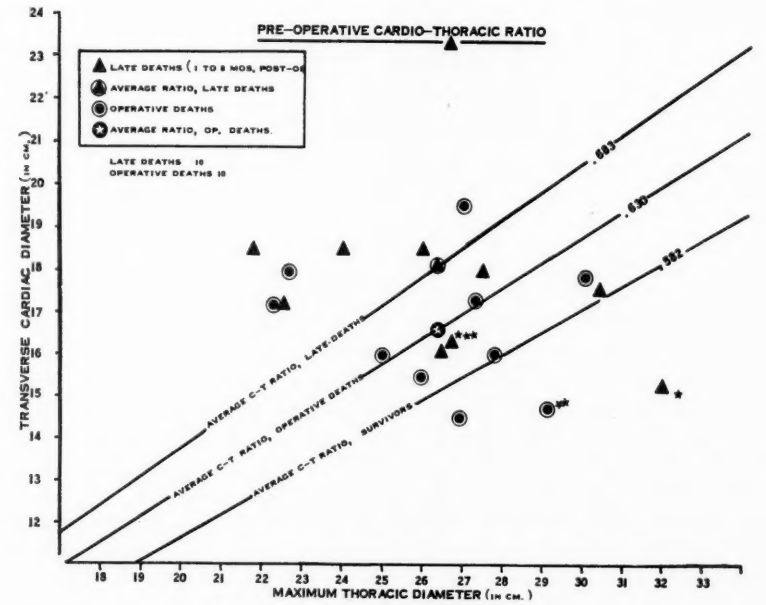

PRE-OPERATIVE CARDIO-THORACIC RATIO
LATE DEATHS (1 TO 8 MOS. POST-OP.)
AVERAGE RATIO, LATE DEATHS
OPERATIVE DEATHS
AVERAGE RATIO, OP. DEATHS.
LATE DEATHS 10
OPERATIVE DEATHS 10
.683
.630
.582
AVERAGE C-T RATIO, LATE DEATHS
AVERAGE C-T RATIO, OPERATIVE DEATHS
AVERAGE C-T RATIO, SURVIVORS
TRANSVERSE CARDIAC DIAMETER (IN CM.)
MAXIMUM THORACIC DIAMETER (IN CM.)

Fig. 2.

responsible for this disturbance. In 5, the electrocardiogram had reverted to the preoperative rhythm by the time of discharge from the hospital (one month). In one case, that of the patient who died 3 months postoperatively with subacute bacterial endocarditis, the conduction disturbance persisted.

OBJECTIVE DATA

In the hope of formulating criteria for the application of corrective surgery for mitral insufficiency, the available data on the subjects of this study has been examined. The 43 patients operated upon have been grouped as follows: 19 patients who are living postoperatively, 14 patients who died one to 8 months after operation, and 10 patients who died within the first week of surgery. This

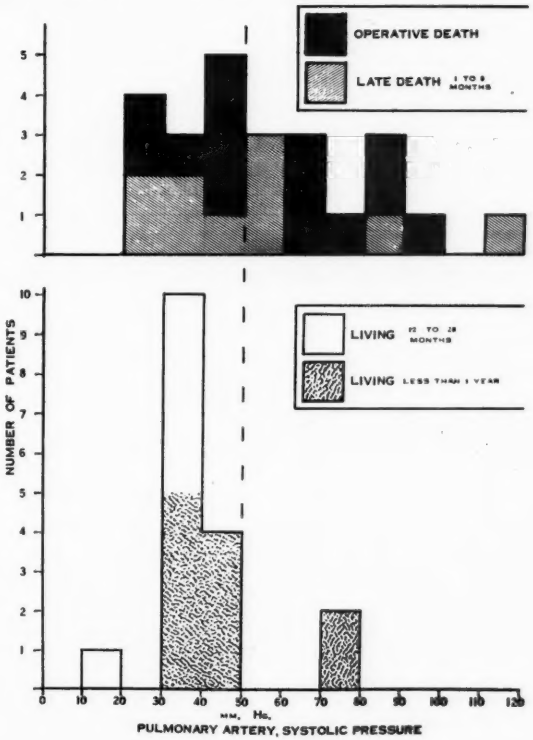

OPERATIVE DEATH
LATE DEATH 1 TO 8 MONTHS
LIVING 12 TO 28 MONTHS
LIVING LESS THAN 1 YEAR
NUMBER OF PATIENTS
0 10 20 30 40 50 60 70 80 90 100 110 120
MM. Hg.
PULMONARY ARTERY, SYSTOLIC PRESSURE

Fig. 3.

eliminates the empirical preoperative evaluation made on clinical grounds. Unfortunately, due to the exigencies of clinical surgery, the information is not uniformly complete. A conscientious effort has been made, however, to gather all possible facts in every case and to subject these data to careful technical criticism.

The influence of age has been tabulated in Fig. 1. Insurance statistics compiled on a group of patients totaling more than 15,000 who had apical systolic murmurs interpreted as organic and who were followed for a period of

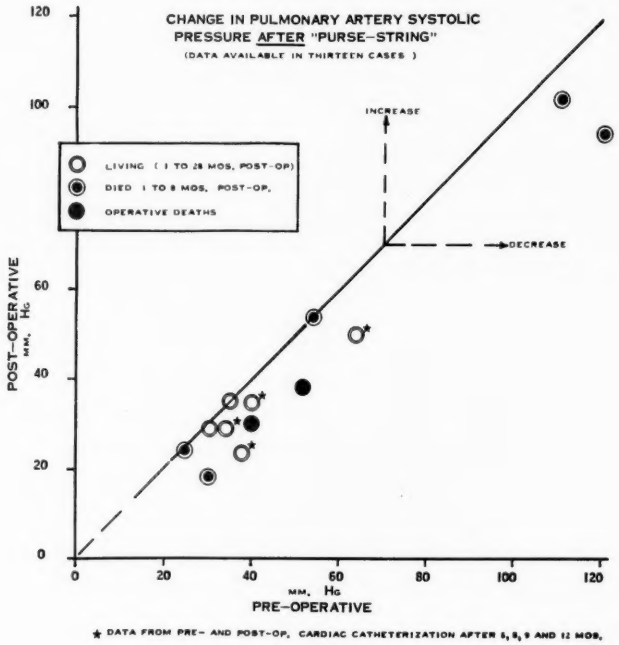


Fig. 4.

Fig. 5.—Extreme and average x-ray and hemodynamic findings in patients of the surviving group.* Left to right. *Top:* Cases 26 and 27. *Center:* Cases 28 and 40. *Bottom:* Cases 38 and 31.

		SURVIVAL†	PA	PVC	LA	LV	LV END DIAST.	ART.	CARDIAC OUTPUT (L./MIN.)	CARDIOTHORACIC RATIO
Average Heart and Average PA Systolic Pressure										
Case 26	Cath.	1 yr.	36/13	32/12	30/17			120/70	2.71	0.661
	Op.				30/12	104/3	8	112/68		
Cas 18	Cath.	1½ yr.	38/18	42/24	42/24	130/8		115/65	8.03?	0.669
	Op.				48/7	120/0	2	125/105		
Smallest and Largest Hearts										
Case 28	Cath.	11 mo.	45/22	12/15	10/0			136/68	3.24	0.464
	Op.				18/5	96/2	7	114/72		
Case 40	Cath.	3 mo.	45/25	35/16	40/17			100/64	2.6	0.663
	Op.				23/11	106/4	10	100/68		
Lowest and Highest PA Systolic Pressure										
Case 38	Cath.	5 mo.	30/12	23/9	26/12			120/68	4.4	0.561
	Op.				30/10	90/12	12			
Case 31	Cath.	10 mo.	70/35	22/15	40/24			120/52	3.3	0.683
	Op.				35/16	96/–4	0	104/60		

*Case 31 died at 1 year. All others are living and well at time of this publication.
†Survival time given at time of presentation (May, 1957).

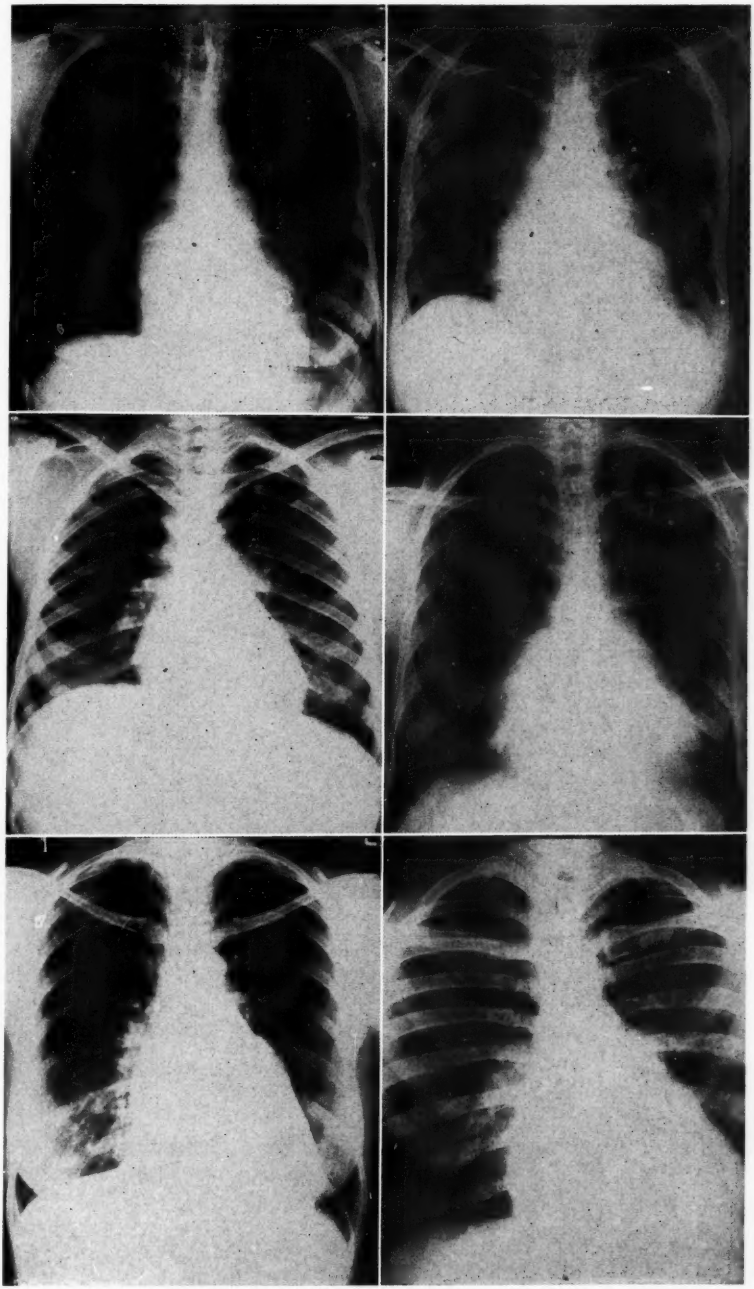


Fig. 5.—*For legend see opposite page.*

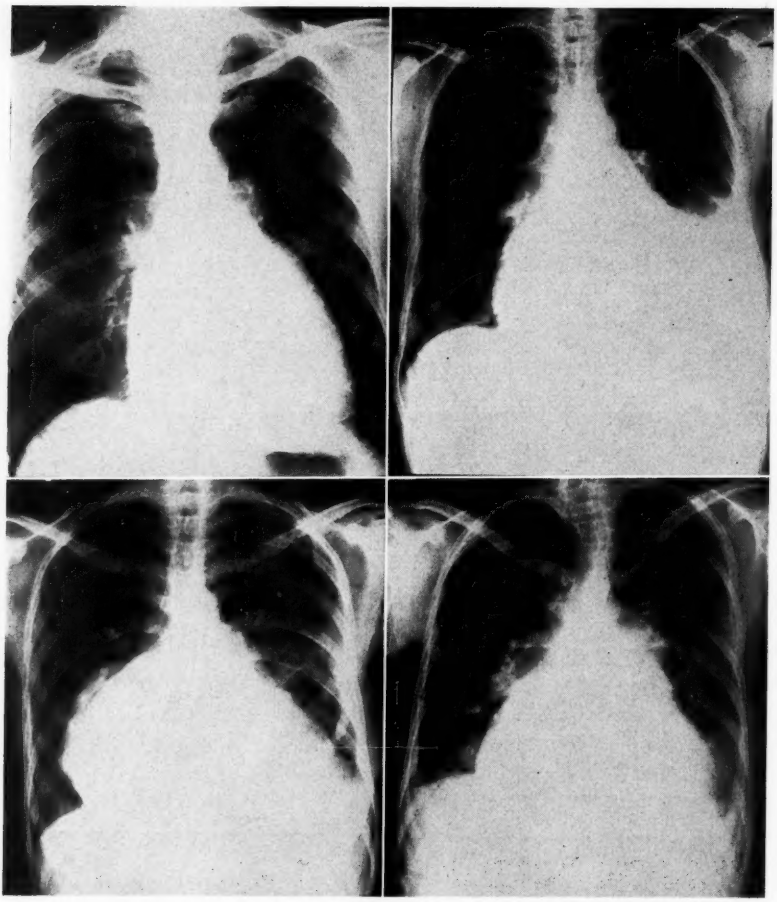


Fig. 6.—Extreme and average x-ray and hemodynamic findings in patients of the late death group. Left to right. *Top:* Cases 39 and 4. *Bottom:* Cases 6 and 8.

		SURVIVAL (MO.)	PA	PVC	LA	LV	LV END DIAST.	ART.	CARDIAC OUTPUT (L./MIN.)	CARDIOTHORACIC RATIO
Smallest Heart Lowest PA Pressure			20/10							
Case 39	Cath.	1½		16/10	35/12			160/68	2.25	0.578
	Op.				30/10	90/12	12			
Average Heart Average PA Pressure			58/30							
Case 4	Cath.	1	54/25							0.756
	Op.				28/11	155/–2	3	130/65		
Largest Heart			28/10							
Case 6	Cath.	2½	48/12	16/5				125/62		0.870
	Op.					80/–8	–4(?)	120/70		
Highest PA Pressure										
Case 8	Cath.	1½	120/60							0.712
	Op.					128/0	10	120/80		

15 years indicate the mortality risk of such individuals. Those who had, in addition to the murmur, moderate cardiac enlargement but gave no history of rheumatic fever had a mortality rate 7.6 times greater than the standard risk. Those who had a definite history of rheumatic fever in addition to the other findings were subject to a mortality risk 11.1 times greater than the standard. If it is assumed that this group largely represents cases of predominant mitral insufficiency, it is evident that we are dealing with a condition which is highly fatal in a relatively short time. The mortality percentage increases abruptly from less than 10 per cent at the 5-year follow-up to 20 per cent at 10 years and nearly 35 per cent at 15 years.* The vast majority of our patients fall between the age limits of 15 to 40 years, the median being 30 to 35 years of age. This group of patients had definite progressive symptoms for an average of 7.7 years, indicating that their lesion perhaps including cardiomegaly was present for even longer periods of time. Their mortality risk then would fall within the limits of the insurance figures quoted above.

It was hoped that x-ray studies might provide a practical means to evaluate the stage of cardiac derangement. The average preoperative cardiothoracic ratio of the living patients is 0.582, that of the operative deaths is 0.630, and that of the late deaths is 0.683 (Fig. 2). Obviously the value of this information is of little significance by itself. It is of importance to note, however, that only 2 of the survivors had hearts larger than the average ratio of the late death group, while 5 of the operative deaths and 2 of the late deaths were above that figure. Also it is of interest that only 3 of the fatalities, one due to incompatible transfusion, and one a late death due to technical error, were below the average ratio of the survivor group.

A correlation of cardiovascular pressures and of heart size by x-ray examination has been attempted in these three groups. Fig. 3 shows the preoperative pulmonary artery systolic pressure in 17 of the survivors and in all of the fatalities. It is not surprising that only 2 patients with pulmonary artery pressures exceeding 50 mm. Hg systolic are living. Yet in 10 patients in whom the information is available the pulmonary artery pressure decreased immediately postoperatively. It remained unchanged in 3 (Fig. 4).

In Figs. 5, 6, and 7 are reproduced the preoperative posteroanterior roentgenograms of average and extreme cases of the living group, the operative deaths, and the late deaths. In the captions are listed the findings of cardiac catheterization, the operative pressures, the cardiothoracic ratio, and the length of survival. There are clear differences in the roentgenograms of the hearts in each group.

Although there is no true correlation between elevation of pulmonary artery pressure and heart size, it is apparent in Fig. 8 that the surviving patients were individuals in whom both cardiac size and pulmonary artery pressure show some relationship, whereas among the fatalities there was wide scatter.

Lung biopsy or autopsy in 22 of 40 cases showed definite pulmonary arteriolar damage in only 4. It is interesting to speculate that pulmonary hypertension in mitral regurgitation is perhaps of more acute onset than it is in mitral

*From: Bolt, W., and Lew, E. A.: Prognostic Valve of Life Insurance Mortality Investigations, Exhibit at A.M.A. Convention, Atlantic City, 1955.

Fig. 7.—*For legend see opposite page.*

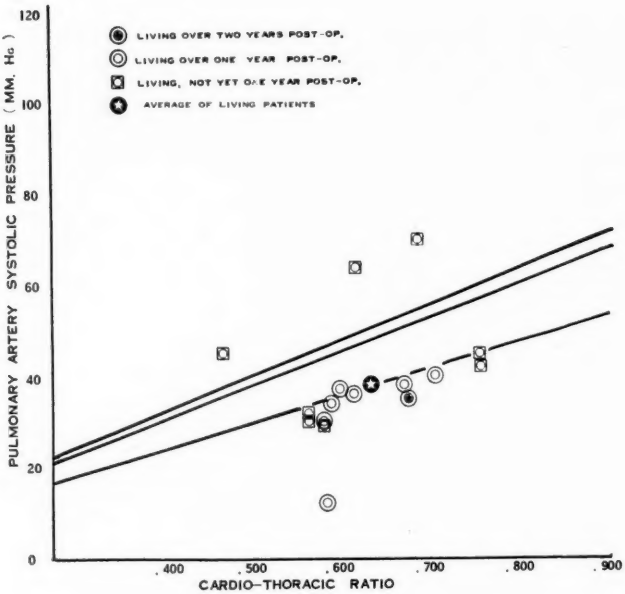
stenosis. Increased impediment to forward flow, concurrent with the inception of left ventricular failure, appears to be more critical than the influence of the regurgitant defect per se in determining pulmonary hypertension. However, there does not seem to be positive correlation between left ventricular end-diastolic and pulmonary artery systolic pressure.

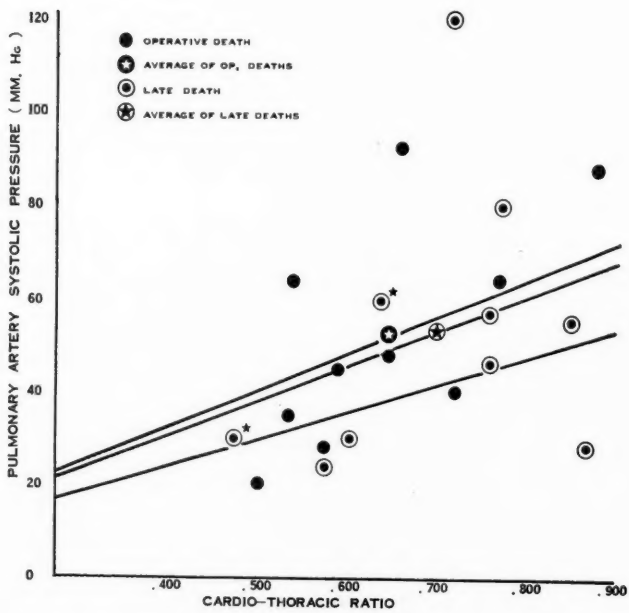
The left ventricular end-diastolic pressure is plotted in Fig. 9 to present the change in this parameter following correction of insufficiency. In 10 of the survivors it decreased significantly. In 4 it did not change (3 of these had essentially normal pressures initially). In 4 others, it increased. Among 14 cases of the fatal group, 7 show an increase. Five of these were operative deaths. Five showed a decrease; these were late deaths. One remained unchanged. None of the survivors had preoperative end-diastolic pressures of more than 14 mm. Hg. Two of the fatalities had higher pressures. The end-diastolic pressure postoperatively in the survivors was above 10 in only 3 cases whereas, in the fatalities, 8 were between 10 and 20 mm. Hg. Five of these were operative deaths. The end-diastolic atrioventricular gradient in 40 of the 43 cases is plotted in Fig. 10. Postoperatively this information is available in only 31 cases, but it is apparent that there is little change in this measurement. The finding of numerous instances of higher left ventricular end-diastolic pressure in the ventricle than in the atrium was unexpected but follows the pattern of grave left ventricular failure with marked increase in initial tension. Among the patients in whom there was a positive gradient, anatomic mitral stenosis was present in only 2. In several others there were varying degrees of commissural fusion of the leaflets but the effective orifice of the valve was ample (indeed, larger than normal in many). In 9 patients, commissurotomy was performed to improve valvular motion, in one to enlarge the effective orifice. The magnitude of regurgitant flow is a function of left ventriculo-atrial systolic

Fig. 7.—Extreme and average x-ray and hemodynamic findings in patients of the operative death group. Left to right. *Top:* Cases 20 and 14. *Center:* Cases 29 and 5. *Bottom:* Cases 36 and 24.

		PA	PVC	LA	LV	LV END DIAST.	ART.	CARDIAC OUTPUT (L./MIN.)	CARDIO-THORACIC RATIO
Smallest Hearts									
Case 20	Cath.	35/17					140/48	4.8	0.536
	Op.			35/10	110/–4	4			
Case 14	Cath.	64/?							0.539
	Op.	52/24		44/10	85/0	8	88/50		
Average Heart and Average PA Systolic Pressure									
Case 29	Cath.	48/30	35/15	50/10			100/60	2.25	0.641
	Op.			48/16	108/–2	5	90/76		
Largest Heart									
Case 5	Cath.	88/35							0.875
	Op.	110/70		38/5	102/–5	18	110/80		
Lowest and Highest PA Systolic Pressure									
Case 36	Cath.	28/10	23/18	24/12			128/64		0.576
	Op.	40/20		35/16	116/4	10	112/74		
Case 24	Cath.	92/44		60/15			140/84	2.3	0.659
	Op.			60/18	120/7	8	124/84		

A.

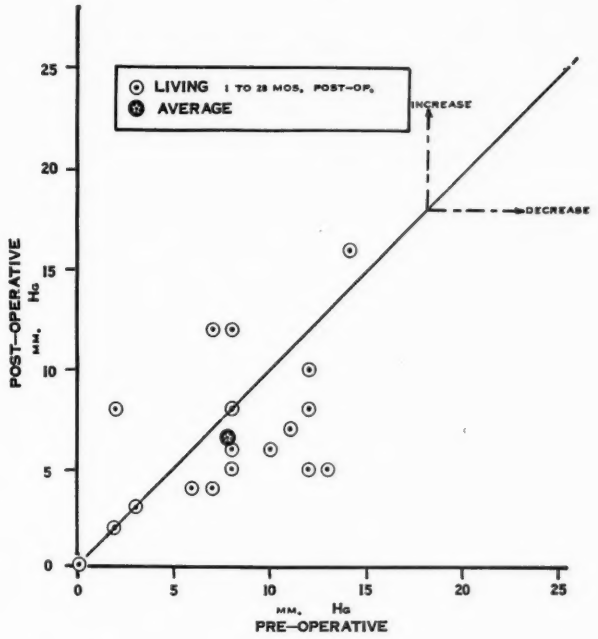


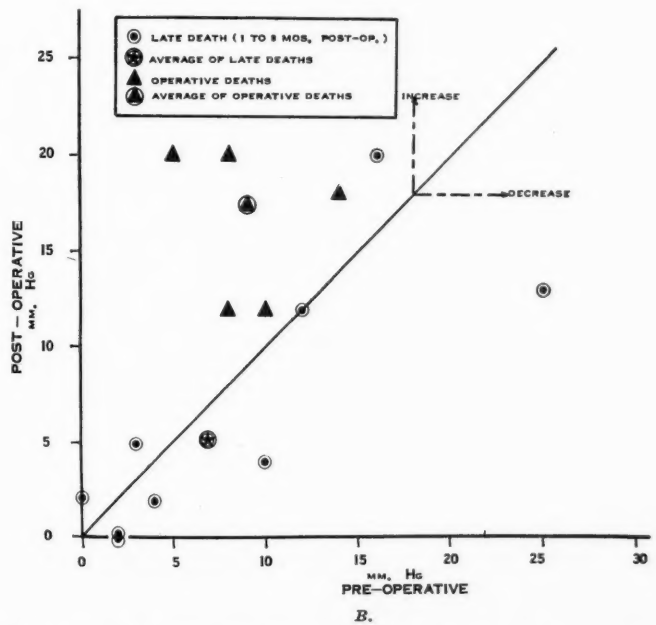


B.

Fig. 8.—In the lower graph (*B*), the asterisks indicate one death by suicide (the uppermost symbol) and one due to technical error.

A.





B.

Fig. 9.—*A*, Left ventricular end-diastolic pressure in 18 living patients, before and after operation. *B*, Left ventricular end-diastolic pressure in 14 patients (5 operative and 9 late deaths), before and after operation.

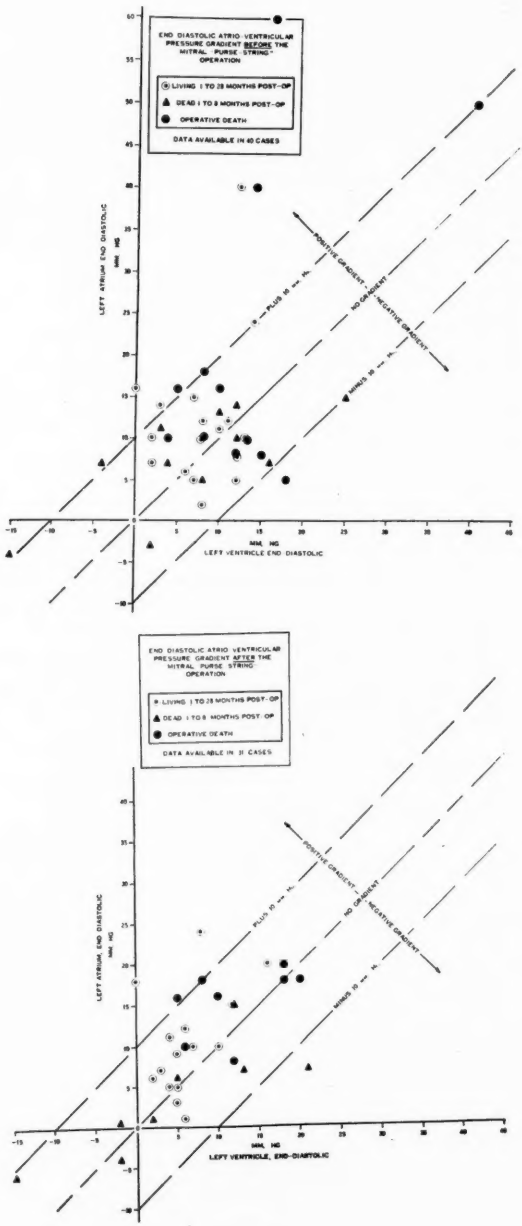

END DIASTOLIC ATRIO VENTRICULAR PRESSURE GRADIENT BEFORE THE MITRAL PURSE-STRING OPERATION
LIVING 1 TO 28 MONTHS POST-OP
DEAD 1 TO 8 MONTHS POST-OP
OPERATIVE DEATH
DATA AVAILABLE IN 40 CASES
POSITIVE GRADIENT
NO GRADIENT
NEGATIVE GRADIENT
PLUS 10 mm. Hg.
MINUS 10 mm. Hg.
LEFT ATRIUM END DIASTOLIC MM. HG
MM. HG
LEFT VENTRICLE END DIASTOLIC
END DIASTOLIC ATRIO VENTRICULAR PRESSURE GRADIENT AFTER THE MITRAL PURSE STRING OPERATION
LIVING 1 TO 28 MONTHS POST-OP
DEAD 1 TO 8 MONTHS POST-OP
OPERATIVE DEATH
DATA AVAILABLE IN 31 CASES
POSITIVE GRADIENT
NO GRADIENT
NEGATIVE GRADIENT
PLUS 10 mm. Hg.
MINUS 10 mm. Hg.
LEFT ATRIUM END DIASTOLIC MM. HG
MM. HG
LEFT VENTRICLE END-DIASTOLIC

Fig. 10.

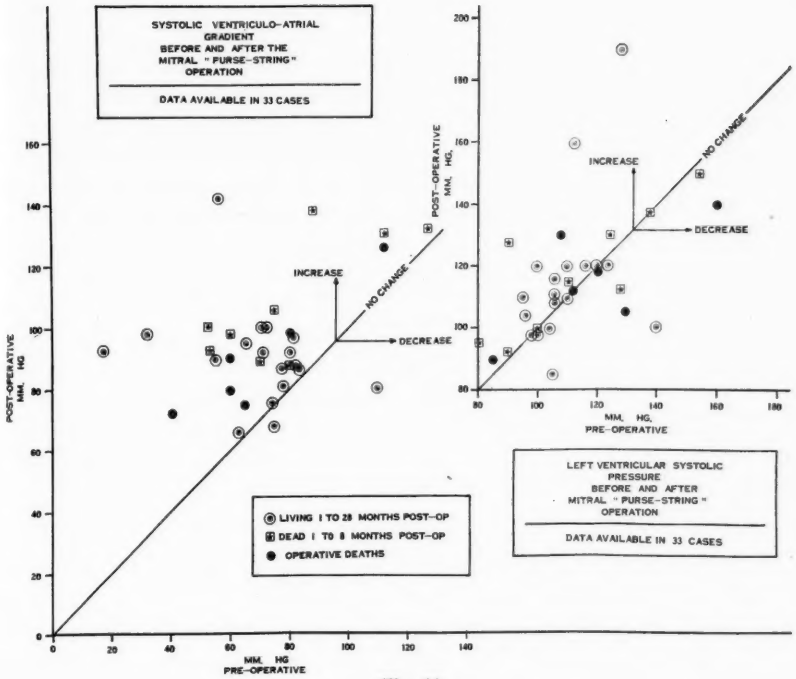

SYSTOLIC VENTRICULO-ATRIAL GRADIENT BEFORE AND AFTER THE MITRAL "PURSE-STRING" OPERATION
DATA AVAILABLE IN 33 CASES
POST-OPERATIVE MM. HG
PRE-OPERATIVE MM. HG
INCREASE
NO CHANGE
DECREASE
LIVING 1 TO 28 MONTHS POST-OP
DEAD 1 TO 8 MONTHS POST-OP
OPERATIVE DEATHS
LEFT VENTRICULAR SYSTOLIC PRESSURE BEFORE AND AFTER MITRAL "PURSE-STRING" OPERATION
DATA AVAILABLE IN 33 CASES

Fig. 11.

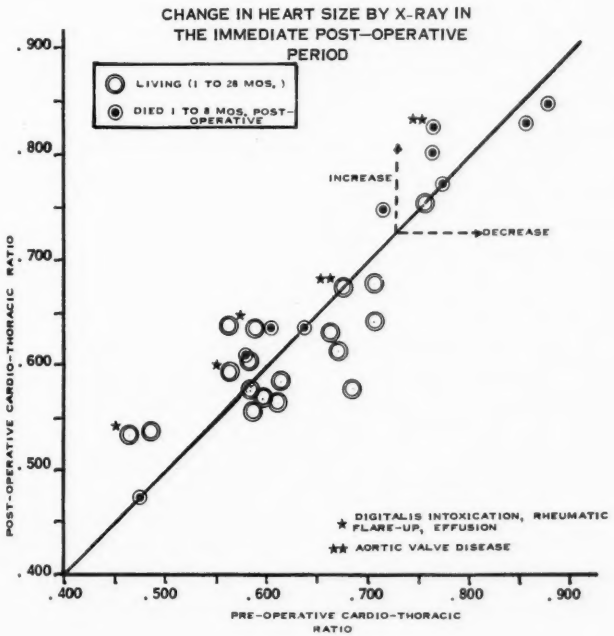

CHANGE IN HEART SIZE BY X-RAY IN THE IMMEDIATE POST-OPERATIVE PERIOD
LIVING (1 TO 28 MOS.)
DIED 1 TO 8 MOS. POST-OPERATIVE
INCREASE
DECREASE
POST-OPERATIVE CARDIO-THORACIC RATIO
PRE-OPERATIVE CARDIO-THORACIC RATIO
★ DIGITALIS INTOXICATION, RHEUMATIC FLARE-UP, EFFUSION
★★ AORTIC VALVE DISEASE

Fig. 12.

gradient and of the size of the regurgitant mitral orifice, as well as of duration of systole. In Fig. 11, this gradient is plotted before and after surgery showing a consistent rise indicating more efficient LV ejection forward against peripheral resistance by virtue of the fact that mitral valvular occlusive resistance has been increased. The gradient rise is partly due to left ventricular systolic pressure rise and partly due to left atrial pressure drop. No significant change in end-diastolic atrioventricular gradient was observed.

Postoperative change in heart size,* as evaluated radiographically, is summarized in Fig. 12.

The consistency with which radiologic reduction of the heart size is seen in the survivors having an uncomplicated postoperative course and the failure of the heart to decrease in size in the late deaths appears to be of some significance. Reduction of heart size in the former group is due obviously to the fact that regurgitation is reduced. In the others, cardiomegally remains unchanged despite reduction of regurgitation and can only be explained on the basis of loss of myocardial contractility.

DISCUSSION AND CONCLUSIONS

The preoperative state of these patients justifies considering at least half of them grave operative risks. On this basis a high operative mortality is to be expected. However, if the "purse-string" operation corrects mitral regurgitation then one would expect good results in the survivors. There is ample evidence that the mechanical defect of mitral insufficiency is corrected by this procedure in the vast majority of the cases. Indeed, patients in less advanced stages of the disease obtain highly satisfactory results. It is, however, the fate of the severely ill patients in whom correction is attained and who survive surgery that is most disconcerting.

It appears that the outcome, in cases like these, may be determined by one of two circumstances: either surgical trauma to the heart cannot be tolerated, or the dynamic changes due to the correction of the regurgitant lesion are such that the gravely damaged heart cannot adjust to them.

In a small number of patients, operative damage to cardiac structures has become evident. Instances of this have been mentioned in which conduction disturbances are demonstrable. The changes are transient, disappearing in a short period of time. Frequently, as in other types of cardiac surgery, electrocardiographic changes compatible with digitalis intoxication, traumatic or rheumatic pericarditis, or myocardial ischemia of minor degrees have been observed. These also are transient changes and serial tracings consistently show reversion to the preoperative state. The possibility of even slight degrees of myocardial ischemia cannot be disregarded, however, and efforts are made to avoid this if such is due to surgical injury. Be that as it may, the operative survival of 29 of 43 patients representing grave surgical risks at the outset would

*Although such a comparison based on the cardiothoracic measurement is subject to the fallacies of this ratio when it involves different cases, it seems less objectionable when it is used to compare individual changes, particularly when the films are made by the same technique in the same institution.

suggest that surgical trauma, well tolerated by the long-term survivors, is of less importance than the physiologic derangement which leads to late death in the most advanced cases.

The dynamics of mitral insufficiency are such that the major cardiac compensatory mechanism must be ventricular dilatation. Increased ventricular volume to accommodate forward stroke volume, regurgitant stroke volume, and residual volume implies extreme degrees of myocardial fiber lengthening. Evidence from animal and in vitro experiments and from clinical measurements indicates that these volumes are considerably larger than has heretofore been thought. It seems likely that in cases, such as some of those here presented, myocardial fiber length has exceeded elastic tolerance and recovery of contractility is not possible. This phenomenon might be compared to the fatigue sustained by inert materials when their tensile or elastic limits are overreached.

In the heart with mitral insufficiency in which the limit of myocardial tension or stretch has not yet been reached, correction of the regurgitant defect results in the following changes: immediate increase in cardiac output, rise in ventricular and aortic mean and systolic pressures, reduction in left ventricular and atrial size (thus, decrease in residual volume), decreased left atrial pressure, and decreased left ventricular initial tension (end-diastolic pressure). The duration of "isometric" or "pre-ejection" phase as well as in that of maximal ejection is observed to increase both in experimental animals and in patients. Heart rate is reduced. All of these changes indicate improved myocardial function. It appears likely that correction of regurgitation results in an increase of effective cardiac work. If this is true, there is also an increase in efficiency of muscular contraction because of shortening of fiber length.

In the far-advanced stages, however, loss of myocardial contractility by, literally, "overstretching" makes impossible reduction in fiber length. Correction of the regurgitant defect increases forward flow and decreases regurgitant flow but may leave residual volume unchanged or even increased. All changes indicative of increased forward flow and reduced regurgitation occur as in the previous group. However, in many of these cases, initial ventricular tension is increased and maximum ventricular systolic pressure may be decreased, even though there is demonstrated a rise in ventriculo-atrial systolic gradient. These changes again imply increased work of the heart, however, contrary to the favorable reduction in muscle fiber length which occurs in the previous group, in these, reduction of ventricular volume (shortening of fiber) fails to occur. Myocardial efficiency then must not improve and, indeed, may deteriorate.

If this hypothesis proves to be correct it poses the problem of either finding ways by which myocardial contractility may be enhanced or of perfecting our ability to select surgical candidates, eliminating those in whom the elastic reserve of the myocardium is exhausted.

Observations that ligation of the vena cava below the renal veins in dogs[7, 8] protects them in the acute phase of experimentally produced mitral regurgitation have led to application of this procedure in 5 severely ill patients. Four of these were cases of intractable mitral insufficiency. The other was a case

of interatrial septal defect with right-to-left shunt. All have shown some degree of early improvement. One of the patients with insufficiency had corrective surgery 6 weeks after vein ligation and has progressed satisfactorily. Fig. 13 illustrates the change in heart size seen in one such patient. The rapid re-establishment of venous collateral circulation appears at this preliminary stage to render this procedure of little palliative value. However, if reduction in heart size is attained in such advanced cases, this might indicate a residual capacity of the myocardium to recover contractility. Inferior cava ligation, then, may be one means of preparing the "intractable" patient for corrective surgery, or it may aid in selecting those patients who may benefit from corrective surgery. It is too early to make any definitive conclusions in this regard.

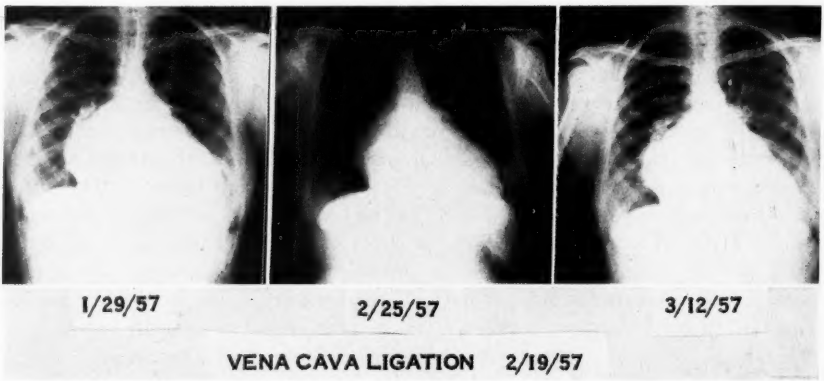


Fig. 13.—Change in heart size following vena cava ligation in a patient of the medically intractable group.

It is apparent that none of the methods used suffice to evaluate the anatomic state of the valve or the functional reserve of the myocardium in mitral insufficiency. Knowledge of both is mandatory if we are to avoid subjecting many patients to fruitless surgery. Fortunately, in pure or predominating mitral insufficiency, the valve is infrequently beyond restoration to adequate function. In this form of regurgitation, however, the muscle is very often irreparably damaged. This represents the greatest problem in the selection of the surgical candidate. Expert interpretation of the ballistocardiogram might offer some useful information. Further experience with the electrocardiographic interpretation of ventricular overloading might similarly be of value. These two techniques have not been adequately investigated with this purpose.

Many workers, ourselves among them, have been engaged in efforts to find a reliable means of quantitating regurgitant volume in the hope that this will prove a useful "yardstick." Our experience with various methods has been disappointing. Direct measurement of regurgitant flow in animals is impractical and unreliable. Direct measurement in vitro, using autopsy hearts on the pulse-duplicator, has yielded figures for regurgitant flow of some two

to four times forward flow.[12] This, however, has only indirect application to clinical practice. Since, in patients, direct measurement is highly impractical and dangerous, indicator dilution studies are currently the most promising means of obtaining such data. Preliminary work in this regard has produced some interesting but inconclusive results.[12] An example of such a study is illustrated in Fig. 14. However, the problem of fractionating the measurement of central dilution to separate quantitatively not only forward flow from central volume but also left ventricular and atrial residual volumes from regurgitant flow remains to be solved. This is of particular importance when cardiac size influences dilution to the degrees that it does in serious mitral insufficiency. For this reason, at the present time, serial injections of Evans blue dye into the ascending aorta, the left ventricle, and the left atrium afford only partial information.[12]

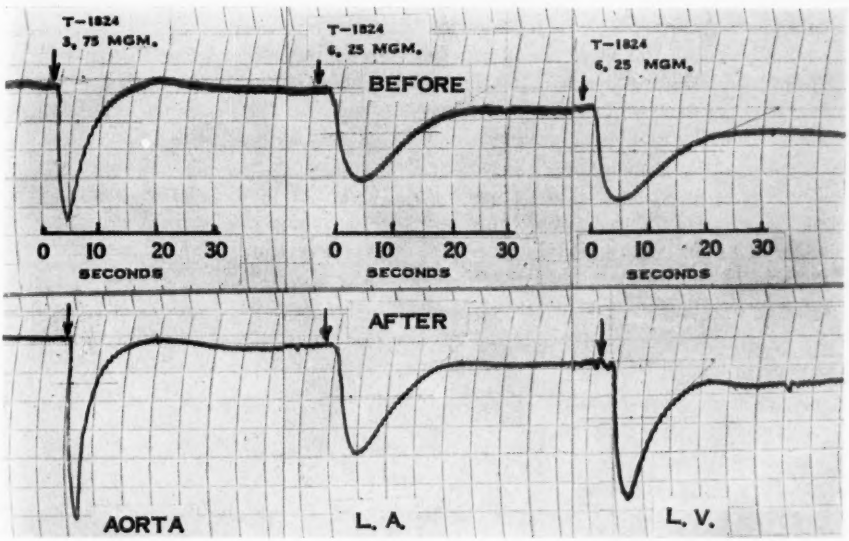


Fig. 14.—Indicator dilution curves of serial injections before and after correction of regurgitation. Although after correction of the lesion, cardiac output, calculated from curves of the aortic injection, is more than tripled, the change in the curves of ventricular and atrial injection can only be evaluated in terms of total central volume without specific fractionation into residual and regurgitant volumes. In this instance, regurgitation was markedly diminished but not abolished, change in ventricular size was also clearly seen.

The inconsistency of the usual objective data has been such that selection of patients for surgery remains difficult and uncertain. It is now known that in certain patients with extremely high pulmonary artery pressure, enormous hearts, and markedly elevated left ventricular end-diastolic pressure, corrective surgery alone, no matter how effective mechanically, is contraindicated. There is, however, much overlap in these findings among patients who have obtained the greatest or the least benefit. Other data such as ventricular strain patterns on electrocardiography, pulmonary wedge or left atrial and left ventricular

pressure pulses is useful only in making the qualitative diagnosis of mitral insufficiency which, in almost every instance in this series, was clinically obvious initially.

The clinical history is of little, if some, help in arriving at a surgical decision. Patients with the longest history of progressive incapacity generally represent the greatest risks. However, a few individuals with cardiomegaly of neither extreme but with histories of more than 10 or 15 years of symptoms do well. Others with enormous hearts but only recent onset of severe incapacity also do well. The response to medical management exhibited by most of these patients has been uniformly unsatisfactory in the intractable group and devoid of significant features in the other group.

The lessons learned at operation have been of the greatest value. It is now quite apparent upon examining some hearts that tolerance to surgical manipulation is out of the question. Others impress one with almost complete certainty of success. Recent experiences have borne out these impressions. The over-all size of the heart is of relatively little importance except when there is obvious left ventricular dilatation. This is frequently accentuated on opening the pericardium. The appearance of such hearts suggests the shape of a Rugby ball. In these, the muscle is thin and tense, pale or mottled. It is apparent to the eye and hand that contraction is weakened and of short stroke. Rhythm is unstable. Slight superficial stimuli and manipulation induce runs of bigeminal pulse, idioventricular beats, or even ventricular flutter or fibrillation. The patients' circulatory balance is precarious under anesthesia and supportive measures are almost routinely necessary.

In patients that do well, the heart has the contour of an acorn. The left atrium may be enormous but the ventricle is relatively small, pink, contracts strongly, and can be seen to "shrink" in systole.

It is unfortunate that, up to the present time, the final decision of whether or not corrective surgery for mitral insufficiency is compatible with recovery and benefit has necessitated thoracotomy in patients who fall in the mid-zones of objective preoperative evaluation. It is obvious that regardless of other circumstances and of the surgical methods used, if valvular tissues have undergone severe destruction, restoration of existing valve elments to function is impossible. On the other hand, with a myocardium which has not been damaged beyond its tolerance, if leaflet structure is available, retains adequate area and flexibility, and can be mobilized, there is no doubt that reduction of the size of the annulus restores, according to the individual circumstances, the maximum possible degree of valvular competence and reverses the insidious dynamic process of mitral regurgitation.

SUMMARY

Circumferential suture of the mitral valve has been used to correct mitral insufficiency in 43 of 49 patients in far-advanced stages of the disease.

A summary of objective and clinical findings preoperatively, at surgery, postoperatively, and of the results obtained is presented.

An attempt is made to correlate objective data available with the results of surgical management.

It is concluded that:

Pure or predominant mitral insufficiency can be corrected mechanically provided valvular area, mobility, and flexibility are retained.

Despite satisfactory correction of the regurgitant lesion, lasting benefit cannot be expected in cases where myocardial contractility is destroyed by compensatory overdilatation.

When valvular damage is excessive and myocardial exhaustion has supervened, surgical intervention, regardless of the method used, can be of no value.

If surgical treatment is to be successful in the advanced stages of the disease, means must be sought to improve myocardial function. Vena cava ligation may be of some value in this regard.

Proper selection of cases should make possible the reduction of operative mortality, the elimination of late deaths, and should lead to the attainment of consistent and highly satisfactory results.

Current methods of preoperative study, both clinical and objective, are inadequate to evaluate the state of the myocardium.

The size of the heart by x-ray examination, the degree of pulmonary hypertension, and the left ventricular end-diastolic pressure are the only parameters which correlate in any manner with the results of surgery.

The clinical and operative findings, particularly the latter, are currently our most useful guide to prognosis.

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Discussion

(Papers by Taylor [page 192], Davila [page 206] and their associates)

DR. BENSON B. ROE, San Francisco, Calif.—Dr. Taylor and the group at the Peter Bent Brigham Hospital, as well as Dr. Lillehei, Dr. Swan, and many others, are certainly to be congratulated on the excellent results in their carefully selected cases with these ingenious methods and on taking advantage of open heart techniques for the approach to the aortic valve in correction of regurgitation. I believe, however, that everyone will agree that the extensive disease that takes place in many of these valves destroys the function of the valve which, in many instances, will never respond to reconstructive techniques and can be corrected only by the insertion of a suitable prosthesis. This challenging problem has been of interest to me for several years and, after many changes of design and many details of construction which time does not permit discussing, I would like to present to you our presently used valve.

This is a prosthetic valve made of a silicone pure material which is flexible. It is made cylindrical in shape, is introduced through a distal aortotomy, and its long axial length maintains its position as it is pushed over the aortic arch to be sutured in place in the ascending aorta. The ring which you see is folded in place and springs back into shape as it reaches the part of the aorta in which it will fit. This is the cut-off valve to show how it can be used in the various direct techniques.

Another design of the valve can be used for subcoronary placement. This merely shows that the valve is competent with only a small amount of leakage, and in the next strip of film you will see that it does leak a small amount of water at high pressure, but what you see at the top is mercury, not water; 300 cm. of water does not blow it out.

This is a film showing the valve with an artificial pumping mechanism to demonstrate that the cusps work. You notice that the upper commissure, for which I must apologize, was not properly prepared and therefore the two upper cusps do not retract properly. This valve was originally reported to be used in polyvinyl material which eventually lost its elasticity, which this material apparently will not do.

DR. F. HENRY ELLIS, JR., Rochester, Minn.—The concept of circumferential suture of the mitral valve ring is an inviting one. Several years ago, when Dr. Davila and Dr. Glover first presented this method before this Association, it appealed to me as being as logical and as promising a method for correction of mitral insufficiency as had yet been suggested. Because their experimental work was done primarily on dogs with acute mitral insufficiency, it seemed wise to us to try to test the method in dogs with chronic mitral insufficiency, a condition more comparable to that seen in man.

Dr. Keykendall, working with dogs in our laboratories, has been able to produce mitral insufficiency which closely resembles that seen in the human being; in other words, dilatation of the mitral ring developed in these dogs, and an enlarged left atrium, and exercise tolerance and so on, were noted. A group of these dogs underwent correction of the mitral insufficiency, and one of the methods used was circumferential suture of the mitral valve ring. It was possible, in 6 of these animals, to abolish completely the mitral insufficiency as determined by disappearance of the regurgitant jet at the time of operation. However, in 5 of 6 animals so treated, within 2 to 6 months after operation, there was a recurrence of mitral insufficiency as evidenced by return of the murmur and the presence of a regurgitant jet at the time of re-exploration.

In no case had the suture cut through into the atrium. However, it had loosened, as it migrated centrally in the tissues of the heart, to lie subendocardially. This experience has discouraged us from applying this method in human beings.

I should like to ask Dr. Davila two questions: Has he used this method in dogs with chronic mitral insufficiency? How often has he seen evidence of the recurrence of mitral insufficiency in patients surviving operation for any length of time?

DR. CHARLES P. BAILEY, Philadelphia, Pa.—[The corrected discussion by Dr. Bailey has not been returned by the discusser.—EDITOR.]

DR. WARREN J. TAYLOR, Boston, Mass. (Closing).—I wish to thank the discussers for their comments.

We too have been concerned, as have Dr. Roe and his associates, with the limitations imposed by the nature of the pathologic valves themselves. The ideal treatment is replacement of the diseased aortic valve by a prosthesis, positioned proximal to the coronary arteries.

Dr. Bailey's comments are pertinent. At one time he made the observation that the base of the aorta spreads and does not taper. Hence, a suture placed about such a cone might tend to "ride up" and threaten the coronary vessels. We have tried to stress the importance of carrying the dissection proximal to the coronary ostia and *below the widest girth of the sinuses of Valsalva.* In our experience, the base of the aorta has always tapered below this point. A suture placed at this level will "ride down" away from the coronary arteries.

We hope that a second point of difference is appreciated. The circumcluding suture is placed *only about the base of the aorta.* Widespread tissue compression, as occurs with the "Sash Operation," is therefore avoided.

DR. JULIO C. DAVILA, Philadelphia, Pa. (Closing).—With regard to Dr. Ellis' question, I would like to say that we do have evidence that patients who have had marked correction of their mechanical valvular defect, even to the abolition of the thrill and murmur, within a matter of a few weeks do show recurrences of the murmur. This is, however, of a mild degree as compared to the preoperative state. We have one patient in whom left atrial pressure is higher several months following correction. We do not know whether this means there is more regurgitation. She is doing very well.

It is extremely important to understand that when the suture is placed it must lie adjacent to the annulus. (slide) This is a section of the mitral ring showing the lateral myocardium, the atrial wall, the base of the valve, the periannular fat pad, the circumflex coronary artery and the cardiac veins. This is the fat pad of the atrioventricular group. The suture is not placed in the myocardium. It is placed beneath the epicardium in the fat pad. When tying the suture it slides over the hump of ventricular myocardium and finds its place in close relationship to the ring. If on tying the suture, it does not come to this position, it will gradually find its way there and therefore will result in some degree of loosening. Evidence collected from a few other patients who have been catheterized, some after long periods of time following the procedure, show that despite the fact that they may have a persisting murmur, their increased cardiac output and their improvement in hemodynamic measurement indicate significant improvement in the regurgitation.

With regard to the statement about whether or not the principle of annular reduction is going to be an adequate solution to this problem, this remains to be seen. Open heart surgery may give us, perhaps, a better way to operate on these cases. It seems, as I said before, that on the basis, not of theory but of repeated demonstration anatomically and physiologically, experimentally and clinically, that this principle is applicable until the time when we can replace the valve, because it does afford the maximum use of what natural valvular elements are available and it does not injure essential valvular structure. It also causes a relaxation of leaflets, allowing better motion.

Any technique which reduces the annulus, whether partially or completely, will restore valvular competence to a degree commensurate with the amount of valvular occluding elements available and with the extent to which these elements are mobilized and spared surgical injury. Any injury to these valvular structures, on the other hand, will result in unpredictable degrees of distortion and mechanical dysfunction.

I would like to thank the discussers for their comments.

CORONARY HEART DISEASE

I. Hemodynamic Principles and Their Therapeutic Applications

B. L. Brofman, M.D. (by invitation), and Claude S. Beck, M.D.
Cleveland, Ohio

DESPITE the most optimistic wishful thinking to the contrary, coronary heart disease continues to be responsible for at least one third of all deaths in the United States,* and may actually be showing a real (rather than merely apparent) increase. The enormous destruction of economic productivity defies statistical analysis. Consequently, with the development of improved methods, there has been a justifiable renewal of interest in the surgical treatment of coronary heart disease. However, lest such efforts be ill advised, particularly in view of the indiscriminate application of such terms as "direct" and "indirect" surgical operation, it would now appear appropriate to attempt to establish a critical definition of the problem and to present a reappraisal of certain fundamental (and often disregarded) principles which determine coronary blood flow to the myocardium.

Although many of the observations and concepts herein presented may appear de novo and perhaps controversial (and are indeed so presented as to stimulate further critical reappraisal), it is pointed out that this presentation is based upon a remarkable experience which encompasses many thousands of laboratory experiments on the coronary circulation, hydraulic model experiments, operations on the heart in more than 300 patients with coronary heart disease, and at least 1,000 other heart operations for various noncoronary conditions. Of profound importance is a unique experience not heretofore available, in patients with coronary heart disease, for direct observations on such hearts. These observations included direct electrocardiographic recording from various epicardial, intramyocardial, and endocardial areas, and extensive hemodynamic studies, including measurements of coronary blood flow, and myocardial utilization of oxygen and various substrates. Thus, we have availed ourselves of a remarkable opportunity for a direct correlation of clinical, experimental, surgical, and pathologic observations.

Certain clinical phenomena associated with a priori reasoning were subjected to laboratory experimentation and, when not substantiated, were then rejected. Of greater importance, clinical observations confirmed by laboratory studies have resulted in the establishment of new concepts which provide a more

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*Latest available statistics from the National Office of Vital Statistics.

logical basis for the therapeutic approach to coronary heart disease. In the constant soul-searching attendant upon such experience, we frequently rejected certain clinical observations which seemed inconsistent with established concepts; however, the constant reproducibility of such observations eventually forced re-examination and ultimate modification of such concepts. Indeed, as recently stated in Lancet, it is hoped that this work "has thrown fresh light on old well-established theoretical concepts."[1]

In the interests of a comprehensive presentation, and yet respecting the limitations of space, much of the material herein presented is necessarily brief, with no attempt at complete elaboration, which we will hope to achieve in subsequent publications.

Its very nature is such that clinical observation is the sine qua non in evaluating the treatment of coronary heart disease. But this disease continues to defy "objective" evaluation. Consequently its treatment has suffered from a great reluctance to make the necessary correlations between clinical and experimental observations. The historical development of present-day comprehension of coronary heart disease is characterized by a disposition to marvel at, and then reject, reproducible and significant clinical observations, rather than to suffer the inconvenience of adapting "well-established" concepts to apparently mutually exclusive observations. As a matter of fact, there exists a general resistance toward positive action under any circumstances. For instance only in recent years has there been universal recognition of the life-saving role of pressor drugs in significantly reducing the heretofore prohibitive mortality in patients with acute myocardial infarction complicated by severe hypotension.[2] The natural reluctance of the physician to transfer laboratory results to the patient has reached its greatest peak of development in the field of coronary heart disease.

Obvious clinical benefit associated with procedures which have adequate laboratory substantiation should not be categorically rejected merely because human coronary heart disease cannot be reproduced exactly in the laboratory, or because its unpredictability defies simple statistical evaluation. Indeed, if need be, it is possible to achieve "progress without statistics."[3]

Even now, during the observation of the Tercentenary of William Harvey's death, many of the significant contributions made since his time are still engulfed in controversy. Furthermore, unless there is adequate reappraisal of certain outmoded concepts, such controversy will always be encouraged by seemingly paradoxical but impressive clinical benefits associated with such dissimiliar agents as nitroglycerin and surgical operation for coronary heart disease. Neither of these presume to produce tremendous alterations in total coronary inflow, but their admittedly limited contributions are critically decisive in the precariously compensated circulation of a potentially ischemic area.

HYDRAULIC CONSIDERATIONS

In a hydraulic system at dynamic equilibrium, the various factors which influence flow can be defined on the basis of simple hydraulic principles

(Poiseuille's law); however, with respect to pulsatile flow in the arteries, these principles should only be applied in rough estimation of these interrelations.[4-7] In the coronary circulation this application is further modified by the influence of extravascular compression. However, for purposes of this presentation, certain generalizations may be derived:

1. Blood flow is proportional to the pressure gradient in a system. Actually, as will be pointed out later, this relationship applies only within certain limits.

2. Flow is also proportional to the square of the cross-sectional area of the vessel, or to the diameter to the fourth power; at critical levels, relatively small changes in the diameter of a vessel may result in profound alterations in blood flow. In hydraulic model experiments, designed to simulate certain aspects of the coronary arterial circulation and using whole blood at body temperature (with no "peripheral resistance"), one-inch segments of hypodermic needles were inserted at the end of the system to produce various degrees of "coronary artery stenosis." Blood flow was measured with simulated "normal" pressure gradients. Average measurements of blood flow are given in Table I merely to indicate semiquantitatively these flow-pressure relationships.

TABLE I. ESTIMATED BLOOD FLOW THROUGH SIMULATED "CORONARY ARTERY" NARROWING

NEEDLE	INTERNAL DIAMETER (MM.)	BLOOD FLOW (VALUES IN DOGS)	
No. 22	0.72	4 c.c./min.	(normal backflow)
No. 20	0.90	8.5 c.c./min.	(backflow after Beck I operation)
No. 18	1.2	34	(circumflex inflow)
No. 15	1.5	100	(total coronary inflow)

3. Blood flow is inversely proportional to the viscosity. Blood with a normal hematocrit has approximately five times the viscous resistance to flow as does water.[8] An increase in hematocrit from 50 per cent to 60 per cent (such as may be associated with polycythemia, dehydration, cold, and emotional states) significantly increases relative viscosity (from 4.5 to 6.5).[9] In a critically compensated coronary circulation, such an increase in resistance to flow may be disastrous.

MEASUREMENTS OF THE CORONARY CIRCULATION

Direct measurement of coronary arterial flow can be carried out in open-chest dogs by means of a rotameter[10] and in closed-chest dogs by means of the nitrous oxide method with coronary sinus catheterization.[11-17] Although direct measurement of flow in man is obviously impractical, the nitrous oxide method with coronary sinus catheterization has provided generally reliable data, although certain considerations, especially in patients with coronary heart disease, may introduce significant errors.[18, 19] In patients undergoing heart surgery, simultaneous sampling from the coronary sinus, pulmonary artery (mixed venous blood), and systemic artery has provided an opportunity to determine oxygen (and other substrate) extraction by the heart, and an index of the adequacy of coronary arterial flow.[20]

In the laboratory,[21] the Mautz-Gregg backflow method, which measures the retrograde flow from the distal segment of an occluded coronary artery, is considered to provide a true measure of interarterial anastomotic function. These retrograde flows are a measure of the collateral bed and serve as a most valuable method for the evaluation of the efficacy of various methods designed to improve collateral circulation. For instance, in a series of 65 control dogs, the average backflow was found to be 3.8 c.c. per minute. In a series of 41 dogs previously operated (Beck I), the average backflow was found to be 8.5 c.c. per minute.

In dogs, the heart weight is estimated to be 0.9 per cent of body weight; so that, in a 15 Kg. dog, the heart weight would be approximately 135 Gm. Coronary arterial flow, which is approximately 5 per cent of the cardiac output, averages 70 c.c. per 100 Gm. of heart weight per minute.[22] Thus, in the 15 Kg. dog, total coronary flow is approximately 100 c.c. per minute. Since the circumflex artery area normally would receive approximately 34 c.c. per minute, the average backflow of approximately 4 c.c. per minute, is 11 per cent of normal inflow into this area. The average backflow of 8.5 c.c. per minute provided by operation is approximately 25 per cent of the normal inflow.

In man, average coronary inflow at rest is approximately 80 c.c. per 100 Gm. left ventricle per minute (approximately 5 per cent of the cardiac output), average oxygen consumption is 9.4 c.c. per 100 Gm. per minute, and the average oxygen extraction is 12 volumes per 100 c.c. of blood flow.[11-13] In an average man, with a cardiac output of 5 L. per minute and a heart weight of 300 Gm., total coronary flow would be approximately 250 c.c. per minute. For purposes of this presentation, let us consider a potentially ischemic circumflex coronary arterial bed with a normal resting flow of 100 c.c. per minute. In this consideration it should be stressed that, generally speaking, the clinical manifestations of coronary heart disease do not result so much from a uniform total reduction in coronary flow as from differences in oxygenation in contiguous areas.[23] As will be amply demonstrated subsequently, there is no obligate relationship between the clinical status of the patient and the total coronary inflow at rest. With a normal total inflow, incapacity and death may occur; on the other hand, in a patient with significant reduction in total inflow, symptoms may be slight or absent.

GRAPHIC REPRESENTATION OF THE CORONARY CIRCULATION

The illustrations herein presented are in the form of stylized graphs, designed to demonstrate flow-pressure relationships in the coronary circulation, with special reference to significant pathophysiologic influences. It should be emphasized that these graphs are obviously oversimplified and are, at best, only semiquantitative. Little consideration has been given to such admittedly significant factors as extravascular compression of the coronary vessels associated with systolic contraction of the heart.[22, 24] In the following part of this presentation, the section number corresponds to the similiarly numbered figure. The detailed description associated with each figure is given in the text.

1. *Normal—At Rest.*—The coronary circulation may be characterized as a high-resistance circuit,[24] in which, merely by an appropriate reduction in vascular resistance, large increases in blood flow to the myocardium are achieved. In a sense, the major coronary arteries serve as relatively passive, wide-bore tubes with a cross-sectional area normally capable of accommodating tremendous increases in blood flow (five to ten times control levels) without significant increases in perfusion (aortic) pressure.[25] For the most part, the sum total of peripheral resistance is normally determined at the level of the arterioles and small terminal arteries[24]; as mediated by metabolic, hormonal, and nervous influences, changes in the smooth muscle of these vessels regulate the bore of the coronary bed.

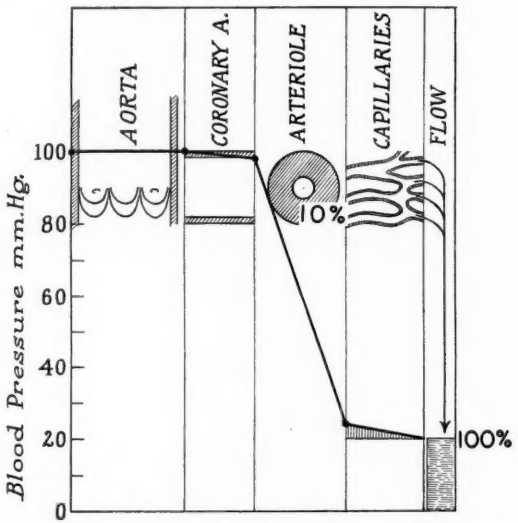

Fig. 1.—Normal—at rest. Stylized graph demonstrating flow-pressure relationships in a coronary bed. Detailed description in text. This and succeeding figures follow the same general motif. The pressure head (in mm. Hg) in each component part of the circulation is represented by the heavy line. In the interest of simplicity, the capillary pressure is assumed to average 20 mm. Hg.[24]

In Fig. 1, mean aortic perfusion pressure is shown on the graph to be 100 mm. Hg (first column). Perfusion of normal coronary arteries is accomplished without loss of pressure head (second column); the cross-sectional area of the major coronary arteries is not a determinant of flow at this level. It is primarily at the arteriolar and terminal arterial level (third column) that coronary blood flow is normally determined. Regulation of flow through the relatively passive capillary bed obtains in the form of an abrupt reduction of the pressure head at the precapillary level. A comparatively small pressure gradient across the capillary bed (fourth column) provides normal flow (fifth column).

2. *Normal—Increased Flow.*—Normally, at rest, myocardial oxygen extraction is so high that increased oxygen consumption by the heart, as during exercise, is achieved primarily by increased flow.[26] This is readily accomplished

by a decrease in arteriolar resistance so that the pressure head arrives at the capillary bed at a higher level. A twofold increase in the arteriolar bed results in a fourfold increase in flow with no significant alteration in perfusion pressure or in major coronary artery cross-sectional area. At extremes of physical exercise or when occlusive disease interferes with coronary flow, an increase in oxygen extraction provides an important compensatory mechanism.[27] (Fig. 2.)

3. *Severe Coronary Stenosis.*—With progressive reduction of the lumen of a major coronary artery, coronary flow at rest is not compromised until the cross-sectional area approaches approximately 10 per cent of normal. At this level, the artery bore also becomes a determinant of coronary flow and reduces the pressure head arriving at the arteriolar bed so that, unless there is a reduction in arteriolar resistance, a deficit in coronary flow results, even at rest.

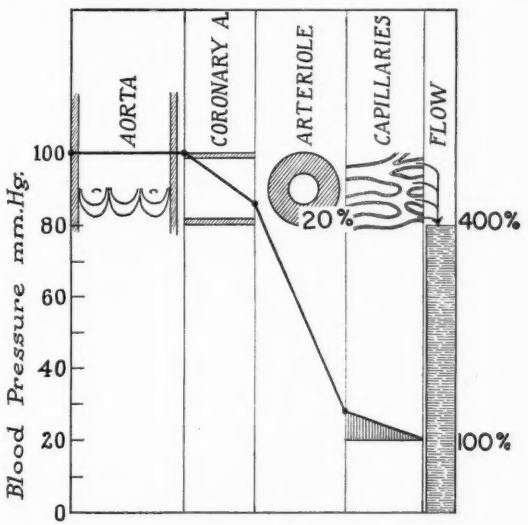

Fig. 2.—Normal—increased flow.

During exercise, in which increased flow is needed, an even greater deficit occurs. In cardiac hypertrophy wherein coronary flow per 100 Gm. of heart muscle is normal,[11] total coronary flow at rest is increased. A reduction in cross-sectional area, which would still allow adequate flow in the normal, causes a deficit in flow in the presence of hypertrophy. (Fig. 3.)

4. *Severe Coronary Stenosis—Compensatory Dilatation.*—At this critical level, the cross-sectional area of the major coronary artery and the arteriolar bed are both determinants of coronary flow; compensatory arteriolar dilatation is still effective in restoring flow to normal at rest (although coronary reserve is obviously reduced). The distribution of coronary blood flow is determined by local resistance. Hypoxia is a powerful coronary vasodilator[27-30]; as a given area

becomes ischemic, its resistance falls, thus encouraging preferential flow to that area. Parenthetically, this reduction in resistance, which is a relative increase in pressure gradients from adjacent beds, also encourages intercoronary collateral blood flow from these regions. (Fig. 4.)

5. *Severe Coronary Stenosis—Exercise.*—Even at this critical level, total coronary flow can still be raised above 100 per cent of normal by maximal

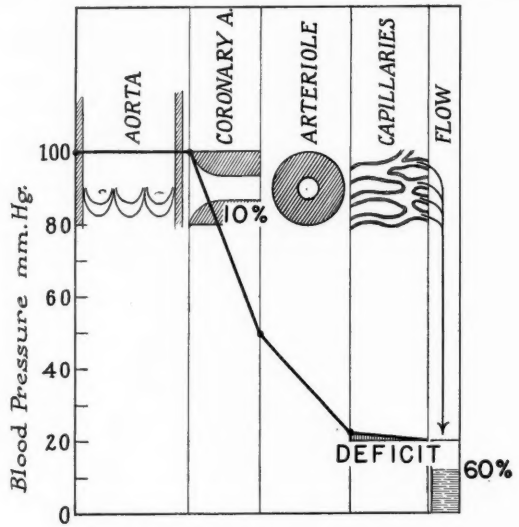

Fig. 3.—Severe coronary stenosis.

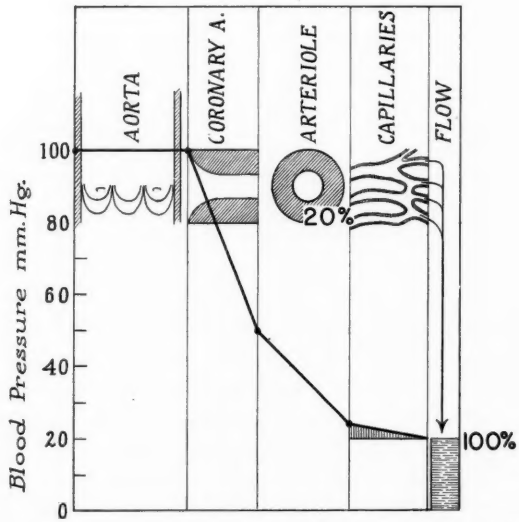

Fig. 4.—Severe coronary stenosis—compensatory anteriolar dilatation.

arteriolar dilatation. Nitroglycerin (as is the case with other true coronary vasodilators) can be shown to exert its effect at the arteriolar level; presumably, its clinical benefit depends upon potentiation of the vasodilatation produced by local ischemia.

However, at those levels of flow in which the arterial stenosis becomes the sole determinant of coronary flow, no further increase in flow is possible despite a maximal reduction in resistance. (Fig. 5.)

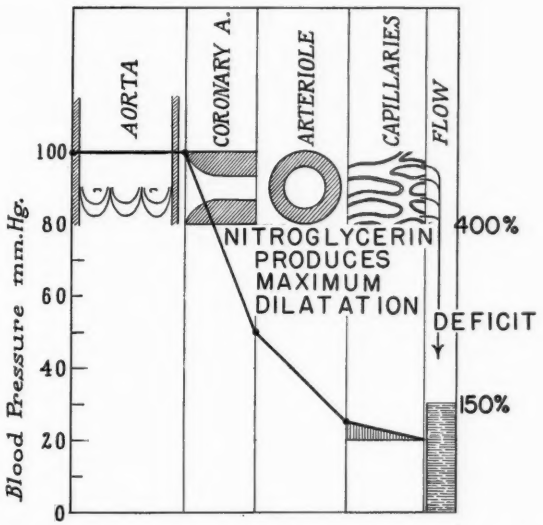

Fig. 5.—Severe coronary stenosis—exercise (400 per cent required).

6. *Very Severe Stenosis—Maximum Arteriolar Dilatation.*—With a slight further reduction in lumen (down to approximately 5 per cent of its cross-sectional area), the major artery now becomes the sole determinant of coronary flow so that, despite maximum arteriolar dilatation, a deficit occurs. Clinically, this marks the onset of (1) status anginosus, (2) sudden death associated with oxygen differentials between the ischemic area and adjacent well-oxygenated areas,[23] and (3) acute myocardial infarction, even without complete artery occlusion. (Fig. 6.)

7. *Very Severe Stenosis—Small Intercoronary.*—With reduction of cross-sectional area below a critical level (even though complete occlusion has not yet occurred), catastrophe is imminent unless adequate development of functional collaterals has preceded the occlusive process. If this has occurred, a potential deficit to a given area may be averted. With an adequate pressure gradient, a group of "small" collateral vessels (however produced) may provide a comparatively abundant blood supply to a potentially ischemic area. For instance, given a large collateral vessel, or a group of vessels, with an aggregate diameter

of 2 mm. and a pressure gradient from the "donor" artery to the "recipient" capillary bed of 80 mm. Hg (100 versus 20 mm. Hg), a blood flow of 50 to 100 c.c. per minute may be achieved, which may well approach the previous normal resting inflow to that area. (Fig. 7.)

8. *Severe Coronary Stenosis—Hypertension.*—In a fundamental sense, the primary determinant of coronary blood flow is the perfusion pressure existing

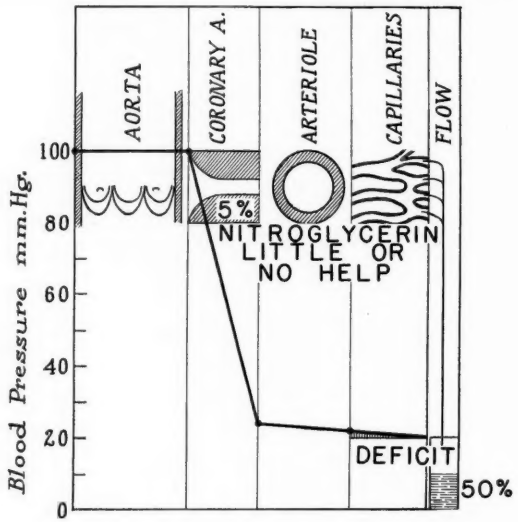

Fig. 6.—Very severe stenosis—maximum arteriolar dilatation.

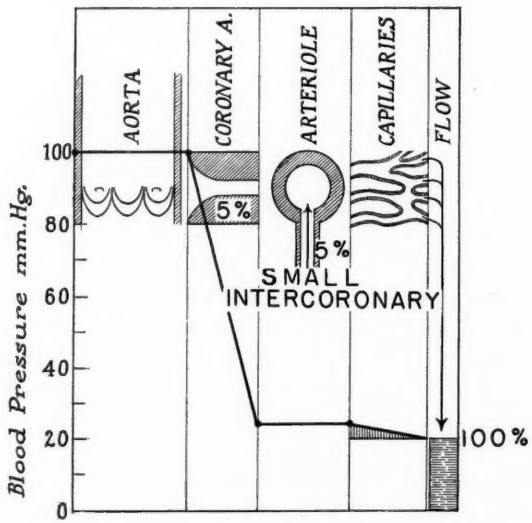

Fig. 7.—Very severe stenosis—small intercoronary.

at the coronary ostia and, more important, the pressure gradient which ultimately drives the blood across the capillary bed. Hypertension, per se, increases the work of the heart and, particularly when cardiac hypertrophy has occurred, myocardial oxygen utilization and coronary blood flow requirements may be many times the normal.[11] Myocardial ischemia may then result from a degree of coronary stenosis which normally would have permitted adequate flow.

When there is severe coronary artery stenosis, an all-or-none relationship may obtain; with normal aortic perfusion pressure, there is no blood flow to a given area, whereas when hypertensive levels are reached, only then, is there achievement of significant blood flow. Regardless of the increased heart work, attainment of an adequate pressure head becomes the most overriding consideration.

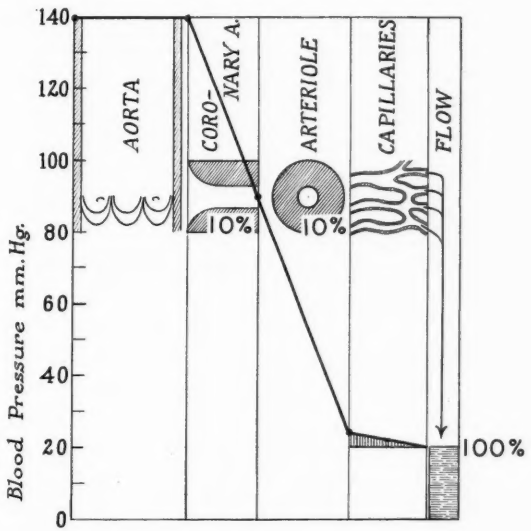

Fig. 8.—Severe coronary stenosis—hypertension.

Fig. 8 is somewhat idealized to emphasize the hemodynamic benefits of increased perfusion pressure. Obviously, the increase in heart work necessary to raise aortic pressure also increases the metabolic needs of the heart. However, in a critically compensated system, the increased flow and increased oxygen extraction provided results in an over-all salutory effect.

9. *Severe Coronary Stenosis—Hypotension.*—Conversely, when reduced below a critical level, perfusion pressure becomes inadequate to overcome viscous resistance to flow and a deleterious relationship is established. Coronary stenosis may produce such a disadvantageous situation at otherwise insignificant reductions in pressure.

Although there is some degree of obligate relationship between blood flow and the pressure gradient, under certain conditions simple hydraulic flow-pressure correlations do not obtain. For instance, for a given pressure gradient,

the variability of vascular distensibility at different perfusion levels may significantly alter blood flow.[31] Normally, viscous resistance is such[5] that the initiation of flow through small vessels requires a pressure gradient of at least 10 mm. Hg (yield pressure). Even in the absence of significant coronary disease, interaction of various factors may increase viscous resistance to flow to such a degree that a given area of myocardium may be rendered ischemic. (Fig. 9.)

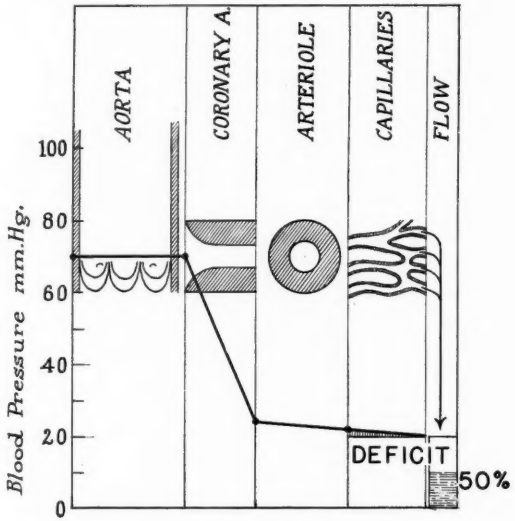

Fig. 9.—Severe coronary stenosis—hypotension.

Clinically, an apparently paradoxical response to antihypertensive therapy has been observed quite frequently.[32, 33] Instead of the anticipated alleviation of symptoms, in patients with hypertension, reduction of blood pressure to "normal" has precipitated symptoms of coronary insufficiency in many patients, with occasional catastrophic consequences. Obviously, in patients with significant coronary artery disease, loss of perfusion pressure in a critically compensated coronary circulation is disadvantageous, even though heart work is decreased. Thus, the medical reduction of aortic pressure is not necessarily desirable.

As previously mentioned, although the deleterious consequences of severe hypotension associated with acute myocardial infarction have long been recognized, the benefit of pressor drugs may still be considered questionable. In producing peripheral vasoconstriction, associated with a relative reduction in coronary resistance,[34] improved perfusion of patent coronary vessels is achieved; previously inadequate vessels may now maintain viability of peripheral regions of the infarcted area in anticipation of the eventual restoration of contractility.

Worthy of consideration as an extreme but not altogether fantastic extension of these considerations, in acute myocardial infarction, elevation of blood

pressure to hypertensive levels may actually be of value in reducing the degree of muscle damage.

VASCULAR REACTIVITY

The coronary vascular bed exhibits a remarkable degree of reactivity in response to various stimulants.[35] Hypoxia or, more specifically, myocardial ischemia is considered to be the primary physiologic regulator of such reactivity.[27-30, 36-39] Even in the presence of severe coronary artery sclerosis, such reactivity is still a major determinant of coronary blood flow.

Many patients with coronary heart disease give a most impressive demonstration of the reactivity of this vascular bed: Soon after arising in the morning, even slight effort results in anginal pain, and necessitates the use of nitroglycerin. As the day progresses, however, with an actual increase in economically productive activity, there is a real reduction in pain so that by evening, unless a large meal is consumed to put an extra load on the circulation, there is less or no discomfort associated with a greater degree of activity than that which produced severe distress earlier. A similar phenomenon is frequently reported from the golf course: At the start, for the first few holes, the patient suffers frequent angina but, as the game progresses, a "second wind" effect supervenes, and the latter part of the game is played with little or no symptoms. This "second wind" phenomenon is related to adaptation and progressive vasodilatation distal to a stenotic area and represents a significant observation of profound practical importance.

In response to various hemodynamic and pharmacologic influences, coronary vasodilatation is quite salutary in some but detrimental in others.[40-47] As has been so well characterized by Gregg and Sabiston,[22] when increased coronary flow is achieved without increased myocardial metabolism, a state of "benign" vasodilatation obtains; however, if increased cardiac metabolism accompanies the increase in flow, this is aptly termed "malignant" dilatation.

In the presence of severe coronary artery stenosis, the adequacy of blood flow to a potentially ischemic area, which is in a state of precarious compensation, depends upon "active" sustained maximal arteriolar dilatation, which in turn is activated by local hypoxia. Any factor (reflex, or otherwise), which even slightly reduces this dilatation, may be catastrophic, despite the fact that vascular resistance may still be much lower than normal.

Despite the remarkable clinical relief afforded by nitroglycerin, its mode of benefit and, indeed, its very respectability have long been suspect; presumably these doubts derive from the misapprehension that dilatation of rigid diseased coronary arteries must obtain in order to increase coronary blood flow.

In the laboratory, such "benign" vasodilators as nitroglycerin can be shown to increase coronary flow, with blood pressure and cardiac output kept constant.[48-53] These vasodilators, per se, appear to have no immediate primary effect on collateral blood flow.[54] Although other specific chemical or metabolic influences of these agents have been implicated,[55] and presumably disproved,[48, 56]

this activity can be logically defined on a purely hemodynamic basis. Incidentally, the remarkable clinical benefit derived from nitroglycerin is further evidence that relatively slight alterations in coronary flow can have profound consequences.

Although there may well be valid objection to its use under special conditions,[57, 58] generally there is little doubt as to its "benign" specificity.[59] By way of "objective" evidence in man, electrocardiographic and ballistocardiograph abnormalities due to coronary insufficiency may be "normalized" by the administration of nitroglycerin.[57-59] A priori, the clinical benefit derived from nitroglycerin is an expression of the potentiation of myocardial ischemia plus nitroglycerin in achieving maximal vasodilatation.

Theoretical arguments to the contrary notwithstanding, prophylactic administration of nitroglycerin actually prevents pain associated with a given amount of activity (by "benign" vasodilatation). Long-term administration of such vasodilators may actually aid in the development of collaterals[60]; however, due consideration is necessary before such may be applied to man.

Blood vessels in different vascular beds react differently under the same circumstances. For instance, in hemorrhagic hypotension, coronary resistance decreases, so that normal coronary flow is maintained; whereas peripheral circulation is decreased.[61] Certainly, vasospastic phenomena are well recognized in peripheral vascular disease,[35, 62] and there is little reason to doubt that such phenomena may well play an important role in the clinical manifestations of coronary heart disease.

Since most coronary catastrophes occur at "rest," it has been assumed that undue stress is rarely the cause, except in certain situations of most strenuous exertion.[63] Contrary to most published reports, in our own history-taking, we have been profoundly impressed by an unexpectedly frequent cause and effect relationship between severe stress and subsequent "heart attacks." which attacks mostly occurred at rest, but the proximate cause appeared undeniable. The fact that there is a period of relative inactivity between the stress and the actual attack should not be allowed to obscure their relationship.

A careful retrospective evaluation of our studies and other published reports[28, 49] reveals a heretofore overlooked, but potentially significant observation: The increase in coronary blood flow, associated with various forms of coronary vasodilator activity, is almost invariably followed by a "rebound," or "dip," phenomenon,[28, 49] so that coronary blood flow is then below normal for extended periods of time. It is merely suggested that such a period of relative vasoconstriction following a period of increased blood flow may well have obvious clinical implications.

It is not altogether fantastic to postulate the following sequence of events: As a given coronary artery progressively narrows, increasing arteriolar dilatation in response to local hypoxia compensates to maintain normal flow to that area. However, eventually, despite maximal dilatation, artery stensis becomes so severe as to reduce inflow into this area, so that the myocardium becomes ischemic, and profound alterations in cellular metabolism occur. Break-down products of ischemia, liberated via the now permeable cell wall either reflexly

or by direct stimulation, produce profound vasoconstriction of the hitherto excessively dilated arterioles, with resultant stasis of blood in the diseased artery. Thus, there is complete obstruction of flow to a given area of myocardium with subsequent necrosis and scar formation. Furthermore, as a result of the sudden development of stasis in the artery, and as an almost incidental secondary phenomenon, thrombosis may occur in that artery segment which is most vulnerable. In other words, that event, toward which we have directed most of our attention as the primary cause of heart attacks, fantastic as it may seem, may conceivably be an incidental by-product of another primary cause.

In this regard, a most intriguing inference is suggested by a series of reports made by European observers.[64, 65] These are concerned with the occurrence of sudden death in at least 50 presumably healthy males engaged in the manufacture of explosives. In each case, there was prolonged continuous exposure to nitroglycol, a volatile nitrite, whose mode of action in man is probably identical with that of nitroglycerin and certain other clinically useful vasodilators.[66] Routine physical examinations a short time prior to these deaths had revealed no significant abnormalities; there was a tendency to bradycardia and slight hypotension; there were no unusual symptoms.

Invariably, sudden death occurred during an unusually prolonged period away from work (vacation or long week end), and appeared to be associated with some degree of mild to marked exertion. The sudden collapse was preceded by precordial distress and "weakness" in some cases. Although it is presumed that death was caused by some form of coronary insufficiency, post-mortem examination revealed essentially normal coronary arteries and myocardium.

These observations have given rise to much speculation,[57, 64-66] none of which appears to account satisfactorily for these sudden deaths. As a logical extension of the concepts herein presented, this intriguing sequence of events lends itself to the following tantalizing explanation: Prolonged exposure to a volatile and potent coronary vasodilator (nitroglycol) had produced in these men a sustained "active" coronary arteriolar dilatation, in which situation the normal physiologic stimuli (hypoxia) were relatively ineffective. Thus, the regulation of vascular resistance was impaired by this "artificial" influence, and had indeed become dependent upon it. When this artificial vasodilator environment was withdrawn, the balance of influences controlling vascular reactivity was disrupted and a "rebound" of relative vasoconstriction ensued. When, in response to the subject's increased activity, normal stimuli to provide the necessary increase in coronary flow were ineffective, a sudden marked deficit occurred, with complete disruption of all myocardial compensatory mechanisms. As a terminal event, arteriolar vasoconstriction may have resulted from this "rebound" phenomenon.

This explanation is not altogether fantastic; similar disturbances in regulation of vital functions abound in clinical states. In pulmonary conditions in which there is alveolar hypoventilation, chronic carbon dioxide retention results in a diminished respiratory response to carbon dioxide. Anoxia, operating via carotid body chemoreceptors, becomes the primary stimulant to breathing. In

such patients, the administration of high concentrations of oxygen, with a rise in arterial oxygen tension, results in reduced ventilation, further carbon dioxide and bicarbonate retention, narcosis, and death.

INTERARTERIAL COMMUNICATIONS

Basically, the extent of coronary arterial occlusion, per se, is not the primary determinant of the clinical manifestations of coronary heart disease; rather, it is the adequacy of the collateral circulation which determines the clinical course.[63, 67-73] Although various other circulatory channels, intra- and extracardiac in origin, have been implicated,[74-80] by and large, the collateral circulation of the myocardium is almost exclusively a function of interarterial anastomoses.

In a fundamental sense, coronary heart disease is a grim tug-of-war, or battle for survival, between the relentless occlusive process on the one hand and a compensating collateral circulation on the other. The patient who develops clinical evidence of coronary heart disease has arrived at this stage of precarious compensation.

Under certain optimum conditions, this delicate balance may be so well preserved that the patient's clinical condition becomes "stable." Generally, this "stability" should not be considered to indicate that, by some miraculous means, the occlusive process has suddenly been halted, but only that it is progressively "neutralized." Thus, the patient is able to maintain economic productivity and well-being almost indefinitely, unless some relatively "insignificant" factor, if only momentarily, upsets this delicate balance and causes death. By the same token, death may be averted by just a little "extra" protection in the right place. Ultimately, with a marked reduction in total coronary inflow, however well distributed, myocardial failure ensues.

Although the excellent studies of Gross,[81] and of Spalteholz,[82] had long ago demonstrated the anatomic features of intercoronary arterial communications, the criterially decisive role of the collateral circulation in protecting the myocardium was not established until the truly momentous work by Blumgart, Schlesinger, and co-workers.[70-73] These studies thus helped dispel the mystery surrounding the inexplicable lack of obligate correlation between the occlusive process in the coronary arteries and the myocardial response thereto.

This monumental work should serve as the logical basis for the therapeutic attack on coronary heart disease; as indeed was well stated in 1951, "Any regimen that would produce interarterial anastomosis so that the coronary arteries were no longer functionally end-arteries would mitigate the clinical manifestations of coronary artery disease. Knowledge of the factors influencing the development of interarterial coronary anastomosis, therefore, would be of great practical value."[72] Unfortunately however, the logical application of these observations in the definitive treatment of coronary heart disease has been obfuscated by a remarkable series of non sequiturs.[83]

In hearts with chronic occlusion of one or even, apparently, of all major coronary arteries, the absence of significant myocardial injury should no longer be considered a medical curiosity which defies scientific explanation, but rather an

impressive demonstration of the tremendous potential for protecting the myocardium provided by adequate intercoronary collaterals. With adequate collaterals to provide uniform distribution via a final common pathway for the ubiquitous red blood cell, the integrity of the myocardium may be maintained almost indefinitely, despite multiple complete coronary artery occlusions.

The activation of collaterals, in response to adequate pressure gradients in adjacent coronary vascular beds, is certainly no more remarkable than many other natural and specific reactions, such as antibody production against a specific infectious agent. The absence of such collaterals[72] in hearts without chronic, complete (or almost complete) coronary artery occlusion is merely an expression of the fact that coronary flow (at rest) to a given area is not compromised until the cross-sectional area is reduced to a small fraction of normal. In response to a given stimulus, there is great variation in man in his ability to develop collaterals. As occurs in other clinical conditions (for instance, susceptibility to carcinoma), this may well be a function of hereditary predisposition. The well-recognized severe disposition, in some families, to a particularly malignant form of coronary heart disease, may actually be a hereditary indisposition to the development of collateral circulation.

Generally, any factor which decreases arteriolar resistance (thereby increasing coronary blood flow), and thus exaggerates pressure gradients from adjacent pre-arteriolar beds, will stimulate increased collateral flow. Such appears to be the case with known stimulators of collateral circulation: anemia[8, 72] anoxia,[72] exercise,[25] and such pharmacologic agents as the nitrites.[60]

Of profound significance is the fact that such procedures as the Beck I operation increase collateral circulation, even in the absence of significant pressure gradients.[84-90] Should there be acute arterial occlusion, such increased collateral circulation, provided in advance, even though it be insufficient to maintain contractility, will maintain viability of the myocardium. The eventual increase in collateral flow to this low pressure bed then restores contractility so that there is no destruction of heart muscle.

There can be little doubt that chronic coronary artery stenosis, with resulting myocardial ischemia, is the stimulus, par excellence, in the activitation of intercoronary arterial communications.[70-73] However, in view of the exorbitant mortality associated with this disease, the assumption that patients with clinical manifestations of coronary heart disease (and myocardial hypoxia) are diligently developing adequate "natural" collaterals is indeed unrealistic. Inherent in such an assumption is the implication that the need for further definitive therapy is obviated. This may perhaps be likened to the following nonsequitor: In a patient with an overwhelming infection, since a specific immune reaction will produce high antibody titers, there is no need for antbiotic therapy.

In view of the remarkable protection provided by a truly adequate collateral circulation, the post-mortem demonstration of "adequate" collaterals in a patient who is dead as a result of coronary heart disease (despite the presence of such collaterals which are presumably more than adequate to prevent death) is apparently paradoxical.

In the presence of truly adequate collaterals, a most remarkable degree of protection is afforded in man.[70, 72, 91] When controlled graded coronary occlusion is carried out in dogs, the development of an adequate collateral circulation enables the animal to survive total occlusion, and may indeed prevent myocardial infarction; in which case there can be no question regarding the far-reaching benefits of a naturally stimulated collateral circulation.[92, 93] Thus, the establishment of adequate intercoronaries, however produced, *in advance* of total occlusion, is truly protective; and any procedure which enhances the establishment of this collateral circulation will provide such far-reaching benefit that this will defy comprehension based upon "established old concepts," in view of the admittedly small amounts of blood made available to potentially ischemic areas.

Although we originally presumed we might help in resolving controversy by means of a more or less unified concept of coronary heart disease, re-evaluation of the role of the collateral circulation has inevitably led us into a new and wholly unexpected development, which might well be considered the last straw in this patently iconoclastic presentation. Heretofore, in the face of all the other raging controversies, the only "sacred cow" in coronary heart disease has been the universally acclaimed collateral circulation. As with the "benign" and "malignant" forms of coronary vascular dilatation, so we find, the collateral circulation itself may well be "benign" or "malignant"!

Adequate intercoronary anastomoses in advance of the occlusive process are truly beneficial; the extensive collaterals resulting from coronary occlusion and myocardial infarction are not necessarily salutary and may actually be deleterious. In encouraging perfusion of a scar, which represents a low resistance bed, a functional arteriovenous fistula may be produced. Preferential flow to this area would then deprive adjacent and still viable myocardium of critically needed blood.

In direct studies during coronary heart surgery, we have found myocardial oxygen extraction (artery-coronary sinus oxygen difference) to be within normal limits, even in patients with severe symptoms of coronary heart disease; however, in those patients with a significant degree of myocardial scarring as a consequence of massive myocardial infarction, the oxygen content in the coronary sinus blood is frequently found to be significantly elevated, indicating a reduction in myocardial oxygen extraction.[20] This apparent paradox is interpreted as further evidence that, in an already compromised coronary circulation, significant amounts of critically needed blood are perfusing the heart without oxygenating the myocardium. Such a phenomenon has been observed by others,[11, 19] but the deleterious significance may have escaped detection.

Clinically, a seemingly inexplicable course of events may well be associated with this concept of malignant collaterals: Following acute myocardial infarction, there is apparent clinical improvement until the tenth to fourteenth day, at which time, rapid deterioration and death supervene. At post-mortem examination, there is no "new" cause for sudden death; the healing infarct and old occlusion, at this stage, are per se, considered as "inadequate" to

account for such circulatory deterioration. It is perhaps more than coincidental that chronologic relations are such that the full development of collateral circulation is generally achieved by this time.[73, 94-98] In patients who survive acute myocardial infarction, "recovery" is marked by gradual circulatory deterioration, with little or no anginal pain, but characterized by easy fatigability, weakness, shortness of breath, tachycardia, reduced pulse pressure, and a relentless downhill course, leading inevitably to death from congestive heart failure. Again, the post-mortem findings are generally considered "inadequate," even by the pathologist, in elucidating this course of events. The amount of heart muscle damage, per se, is inconsistent with the catastrophic clinical consequences. Furthermore, when injection and dissection studies are performed, the collateral circulation is "more than adequate" to prevent death.[70, 97]

If this pernicious influence of postinfarction collaterals (not to be confused with "benign" and remarkably protective preinfarction collaterals) can be adequately substantiated, in addition to the obvious implications of such a profound alteration in a "basic" concept of cardiology, in such patients we will also have the first really valid indication for surgical excision of a myocardial scar or, perhaps, if technically feasible, just ligation of the "malignant" collaterals.

SURGICAL TREATMENT FOR CORONARY HEART DISEASE: DIRECT VS INDIRECT

It is not our intention in this publication to discuss, per se, surgical treatment; however, suffice it to say that, in our desire to achieve the "direct" surgical approach to this disease, we must not disregard certain fundamental (but neglected) considerations with regard to the pathophysiology of coronary heart disease. Such prodigious technical achievements as coronary endarterectomy[99] and anastomotic bypass of arterial occlusion almost pale into insignificance as compared with the other formidable and deceptive pitfalls inherent in this "direct" approach. Presumably, contrast visualization of the coronary arteries in man will eventually be feasible (if somewhat dangerous); thus, in a patient with clinical symptoms of coronary heart disease, "localization" of obstructions in the coronary circulation will allow the surgeon to select at least certain diseased segments for the "direct" approach. (It is unrealistic to anticipate the application of such procedures to more than one, or perhaps two, separate obstructions in a given patient.)

It is axiomatic that there is no obligate relationship between the extent and location of the occlusive process in the coronary arteries and the clinical consequences thereof.[70] Only "moderate" stenosis of one artery may result in death; on the other hand, chronic multiple complete occlusions of two or more arteries may produce no symptoms and, indeed, no myocardial damage. In a fundamental sense, the patient's symptoms are not due to the actual occlusive process in the coronary arteries, but to the response of the myocardium. Coronary occlusion, per se, is not the clinical disease. Even consideration of endarterectomy as an "emergency" procedure is unrealistic. Although coronary thrombectomy is "like thrombectomy for arterial thrombosis elsewhere,"[99] the myocardium is unlike other organs (except, to a certain degree, the brain), in that within 20 to 30 minutes after occlusion irreversible damage has occurred.[70]

In a patient with coronary heart disease, the unwarranted assumption that the functional disturbance is due to a given obstruction of a coronary artery is most ill advised and may have disastrous consequences. Restoration of flow into a given area of myocardium may not only have no beneficial effect but, if flow is restored to a scar in a previously infarcted region, preferential perfusion of a low-resistance area may then deprive viable myocardium of blood which is already in short supply. Thus, a deleterious effect is produced, as may well have been (inadvertently) recently demonstrated.[99]

The patient with coronary heart disease has a precariously balanced circulation; adequate intercoronary collaterals may maintain the dynamic integrity of the heart almost indefinitely. Any procedure which enhances the production of collaterals in advance of the occlusive process will be remarkably effective. On the other hand, a "direct" approach, which may actually disrupt this balance, may have catastrophic consequences.

SUMMARY AND CONCLUSIONS

In a fundamental sense, the dynamics of coronary heart disease may be characterized by the following axioms:

1. The fate of the myocardium, and indeed the fate of the patient, depends upon the amount of blood available to a potentially ischemic area.

2. There is a complete lack of obligate correlation between the degree of occlusive disease in the coronary arteries and the clinical consequences thereof. It has been convincingly demonstrated that complete coronary artery occlusion does not necessarily result in myocardial infarction; myocardial infarction may occur without complete artery occlusion; the site of myocardial infarct is not necessarily related to the site of coronary occlusion.

3. In the presence of a truly adequate intercoronary arterial collateral system, the tremendous potential for preservation of the myocardium is preserved even when total cross-sectional area of the major coronary arteries is profoundly reduced to a mere fraction of normal.

The following can be considered as corollaries to these axioms:

1. The symptoms of coronary heart disease are not necessarily correlated with total coronary inflow.

2. Rejection of the "indirect," and application of the "direct" surgical approach to the problem of coronary heart disease, is frequently based upon the false premise that the disease process has obviously already produced maximum intercoronary communications; therefore, little can be achieved in stimulating more collateral circulation.

3. Generally, it is the uniformity of distribution rather than total inflow that determines the clinical manifestations of coronary heart disease.

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Discussion

DR. BERNARD L. BROFMAN, Cleveland, Ohio (Closing).—There can be little doubt that the ultimate solution to this destructive disease lies in medical prevention of the occlusive process in the coronary arteries. Whatever the ultimate role of surgery in the treatment of coronary heart disease, one of Dr. Beck's most significant contributions in this field has been to encourage the coordinated effort of the medical cardiologist and the cardiac surgeon and in correlating experimental, hemodynamic, clinical, pathophysiologic, and bioelectrical observations and *applying* them for the benefit of the patient. Certainly, without such a comprehensive approach, one cannot achieve a series of 100 consecutive operations without operative mortality; nor can one demonstrate an almost unbelievable degree of *clinical improvement* and *increased longevity* in 9 out of 10 patients operated upon.

[The corrected discussion by Dr. Vineberg has not been returned by the discusser. —Editor]

ATRIOSEPTOPEXY: A SIMPLIFIED NEW TECHNIQUE

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ALTHOUGH closure of human atrial septal defects was first suggested by Cohn[1] in 1947, and was accomplished partially in 1948 by Murray[2] by anterior-posterior suturing of the atrium in the line of the septum, it was not until Jan. 11, 1952[3] that a human atrial septal defect was completely closed by one of us (C. P. B.) as shown by postoperative catheterization. The method amounted essentially to invaginating a portion of the consistently redundant or dilated right atrial wall against the septal defect, to the periphery of which it then was securely sutured under digital guidance. This method of closure was termed "atrioseptopexy." Since its innovation, a number of logical modifications have been devised and applied for the several anatomic variations which may be encountered[4-6] (Fig. 1, *A, B, C*).

Since that time, other methods have been developed and tested extensively. These include the closed method of Sondergaard[7] in which the septal defect is constricted by a circumferentially placed tape or suture, and the semi-open "well" method of Gross[8] which has been elaborated upon by Kirklin.[9] (More recently, Gross[10] has adopted the method of atrioseptopexy for the majority of his cases.) Finally, there are the open techniques of Lewis and Taufic,[11, 12] and Swan,[13] using hypothermia, and of Gibbon,[14] DeWall,[15] and others using cardiac by-pass with a pump-oxygenator.

Although these latter techniques in time may prove to be applicable and safe for this purpose, their very considerable presently existing hazards have led us to restrict their use to the more complicated intracardiac lesions which are not remediable by closed methods. Atrioseptopexy, in our hands, has proved both safe and practicable, and has been employed routinely by us with good results in properly selected cases of ostium secundum defect (Table I). We have had poor results in patients with ostium primum lesions, and prefer to operate upon these by an open technique using a pump-oxygenator.[16] Also, we have had poor results in patients in whom the shunt has become either

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reversed or balanced,[6] apparently because of the extreme pulmonary vascular change which has taken place. We feel that these patients have become irretrievable by any surgical means.

TABLE I. RESULTS OF ATRIOSEPTOPEXY IN OSTIUM SECUNDUM PATIENTS WITH A LEFT-TO-RIGHT SHUNT OF MORE THAN 1.5 LITERS PER MINUTE

NUMBER OF CASES	NUMBER OF DEATHS	PERCENTAGE MORTALITY	POSTOPERATIVE CATHETERIZATION	NUMBER CLOSED	PERCENTAGE OF CLOSURE
74	4	5	40	38	95

Because of the low mortality (5 per cent) and the high number of successful closures (95 per cent by catheterization) which is obtained by atrioseptopexy, we feel that this is the method of choice at the present time.

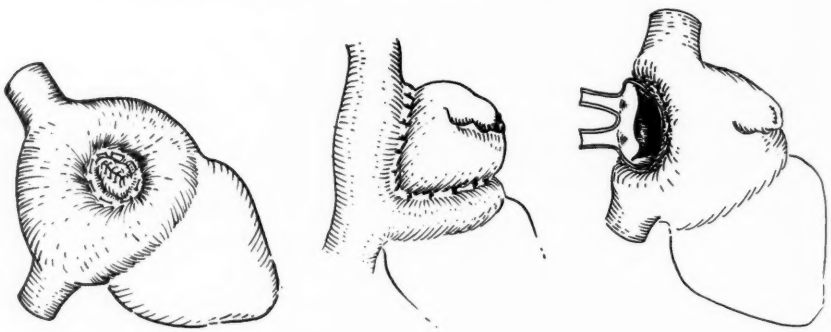


Fig. 1.—*A*, Classical atrioseptopexy. Invagination of the redundant right atrial wall and suture approximation to the periphery of the defect, suitable for moderate-sized central defects.

B, Atrioseptopexy which displaces the effective right atrial chamber posterior and caudad to the defect which remains anatomically existent.

C, Atrioseptopexy for retransposition of anomalous right pulmonary veins after enlargement of septal defect. If none exists, one may be created by the use of the cardioscope or by a bistoury knife and scissors (guided by the intracardiac finger).

However, at times, one of us (C. P. B.) has experienced considerable technical difficulty in performing this operation, particularly when the right atrial chamber is very large and the lower (caudad) portion of the atrial septal remnant lies very deep within the atrial cavity. Should this septal ridge prove to be small or unusually fragile, it may be nearly impossible to pass a properly directed needle through both the lateral atrial wall and this tissue at the same time. Tearing of the septal margin has resulted from persistence in such effort and, on one occasion, has been responsible for the persistence of a small residual interatrial communication.

For these reasons, we would like to present what we feel is a significant advance, first suggested by the senior author (T. H.), in the technique of performing atrioseptopexy. In brief, this consists of introducing the guiding left index finger into the *left* atrium from the right side of the heart, so that it lies behind or to the left of the defect, instead of introducing it through the right auricular appendage, as has been our custom previously. This method of

entrance into the left atrium from the right side is the same as that which we have described for the performance of mitral commissurotomy from the right side.[17, 18] Since it is not necessary to constrict the base of the auricular appendage with a purse-string suture, a significantly greater amount of right atrial wall thereby is rendered available for the septal repair.

With the intracardiac finger tip inserted to the left of the septal remnant and with the left thumb outside of the dilated atrium, it is easy to bring into apposition the lateral septal wall and the rim of the defect, thus greatly facilitating the placement of sutures for permanent closure of the defect. Rather small suturing needles (curved) are satisfactory once these two tissue layers have been brought into neat contact.

OPERATIVE TECHNIQUE

The patient is placed upon the operating table in the supine position, and a curved submammary incision is made from the right sternal border to the mid-axilla. The fibers of the pectoralis major muscle are separated and divided as necessary, and the right fourth intercostal space is opened. The internal mammary vessels are divided individually and ligated. If necessary, the costal cartilage of the fourth rib is separated from its sternal attachment to increase the exposure.

The pericardial sac is incised longitudinally just anterior to the phrenic nerve. The lower extremity of this incision is angulated forward to the sternal margin to obtain a wide exposure of the right atrium. By manual retraction of the right atrium with a gauze pad medially and anteriorly, by an assistant's hand, the interatrial groove is exposed.

The epicardium covering this interatrial fossa is dissected longitudinally for a distance of 1.5 cm. in the line of the groove, and to a depth of approximately 1 cm. It is encircled widely by a No. 2 nylon purse-string suture placed deeply into (actually through) the respective atrial walls on each side of the groove. The suture is incorporated within a Rumel-Belmont tourniquet for flexible reliable hemostatic control. Using a swedged-on curved needle, a No. 3-0 cotton stitch is placed just beyond either extremity of the dissection in such a way as to hold the two atria together, thus obviating any tendency toward spontaneous further separation. The ends of these stay sutures are left long.

A heavy (No. 2) braided nylon suture with a swedged-on curved needle is passed and repassed through the everted lips of the epicardial incision in such a way as to ensure later eversion of the to-be-incised septal aspect of the left atrial wall after the intracardiac manipulations through this entry portal have been completed (Fig. 2).

With a special sharp-pointed Morse* scissors (Fig. 3), which also have slightly sharpened external edges, a longitudinal stab wound is made into the now exposed septal portion of the left atrial wall (Fig. 4). The blades of the scissors are spread to make a longitudinal slit which will allow entrance of the tip of the left index finger.

*Obtainable from Geo. P. Pilling & Son Co., Philadelphia, Pa.

The operator's ungloved left index finger is bathed in a dilute (1/10,000) heparin solution and is inserted, palmar surface upward, into the incision in the

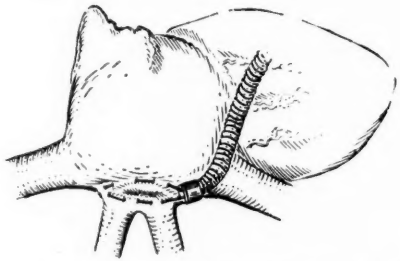


Fig. 2.—Lateral view of right side of heart with the patient face up, showing the location of the purse-string suture about the interatrial groove.

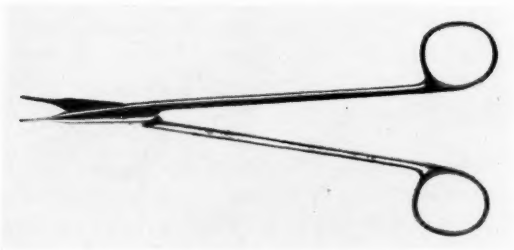


Fig. 3.—Photograph of Morse scissors.

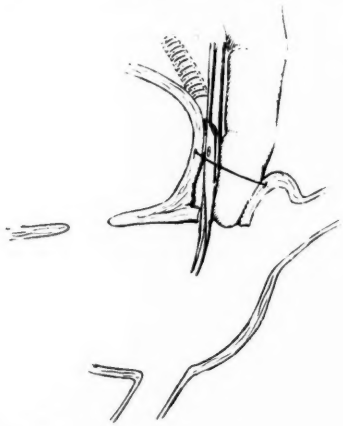


Fig. 4.—Transverse section showing entrance of pointed scissors followed by finger into left atrium in the posterior portion of interatrial groove.

atrial wall tamponading the bleeding which also is restrained by slight tension applied to the purse-string suture. The finger tip is advanced gently, the tourniquet tension being modified appropriately.

After careful palpation of the septal defect, all normal or abnormal pulmonary vein ostia, the mitral and tricuspid valves, and the vena caval and

coronary sinus ostia, the right atrial wall is compressed down upon the defect by the operator's left thumb (Figs. 5 and 6). The intracardiac left index fingertip holds the septal margin up against the partially invaginated left atrial wall. Provision is made for preservation of an adequate intra-atrial passageway for both the superior and inferior vena caval blood flow to the tricuspid valve. This passage may be placed either anterior or posterior to the region

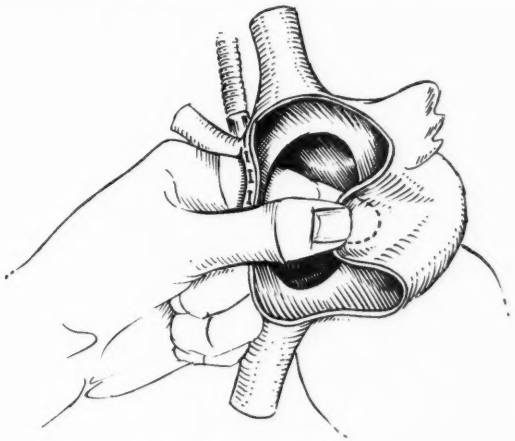


Fig. 5.—Anteroposterior view showing approximation of right atrial wall to the edge of the defect by the intracardiac (left atrial) index finger apposing the extracardiac thumb.

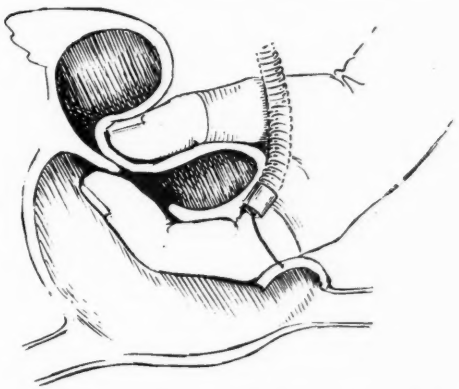


Fig. 6.—Cross section showing approximation of right atrial wall to the edges of defect.

of atrioseptal approximation, whichever is more convenient. In some cases, when the defect lies centrally, both an anterior and a posterior channel for blood flow is provided (see Fig. 1, *A*).

A heavy nylon suture on a small curved Atraumatic needle is passed through the external atrial wall into the atrial lumen, then, through the adjacent margin of the septal defect and out again through the atrial wall, forming either a simple or, preferably, a mattress type of approximating stitch. This

suture is easily placed by the guidance of the intra-atrial index finger. The actual or near approximation of the structures being sutured renders facile the passage of the needle (usually in a single arcuate movement). Preferably, each successive suture is applied into the margin of the defect in an overlapping fashion, so that one half of that portion of the septal and atrial walls approximated by the previous suture is also included in the subsequent one. Several such sutures may be placed before any are tied. When they are drawn down together, the distribution of tension tends to prevent any tearing out of the sometimes delicate septal edge.

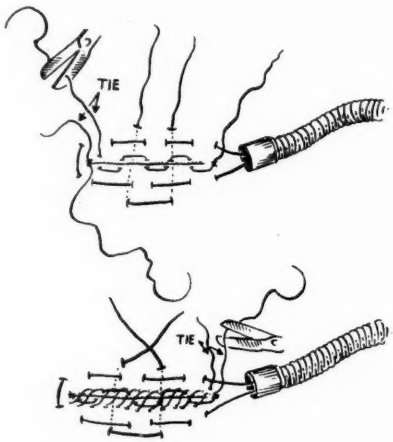


Fig. 7.—Closure of dissected interatrial groove with continuous everting cotton sutures.

After the septal closure has been accomplished, as the intracardiac finger is withdrawn, the original nylon everting mattress suture placed across the dissected interatrial grove is tightened. This eversion ensures the endocardium-to-endocardium approximation of the lips of the left atrial incision which is necessary to prevent the formation of an intra-atrial thrombus. The two external lips of the dissected interatrial groove are secured with a row of continuous everting cotton sutures and a second row of running over-and-over sutures, employing the previously placed stay sutures which have been left long with the needles attached (Fig. 7).

TABLE II. CONCOMITANT LESIONS IN 83 CASES OF ATRIAL SEPTAL DEFECT (SECUNDUM TYPE)

LESION	NUMBER OF CASES	PERCENTAGE
Uncomplicated (by other cardiac lesion)	59	71.1
Associated anomalous pulmonary venous drainage	15	18.1
Associated mitral stenosis	8	9.6
Anomalous veins and mitral stenosis	1	1.2
Total	83	100.0

MODIFICATIONS OF TECHNIQUE (Table II)

Coexisting Anomalous Right Pulmonary Venous Drainage.—The orifices of any such veins which enter directly into the right atrium may be diverted into

the left atrium by invaginating the vein-bearing portion of the right atrial wall against the usually conveniently located septal defect. If the defect does not lie in close proximity to the mouths of the anomalous veins, one may be made in an appropriate location by deliberately incising the septum. Then, the vein-bearing portion of the atrial wall may be sutured against the region of the created septal defect (Fig. 8). In either event, the anomalous veins are caused to drain directly into the left atrium while the vena caval flow is separated from it. A similar technique may be used for the correction of anomalous drainage of the right pulmonary veins in the absence of any septal defect.[19]

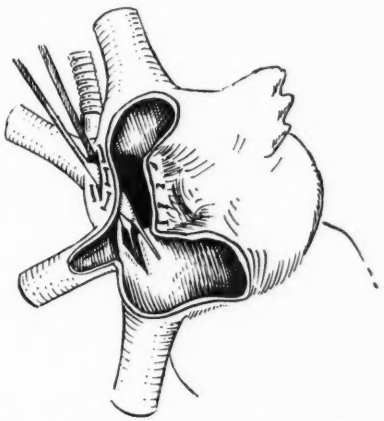
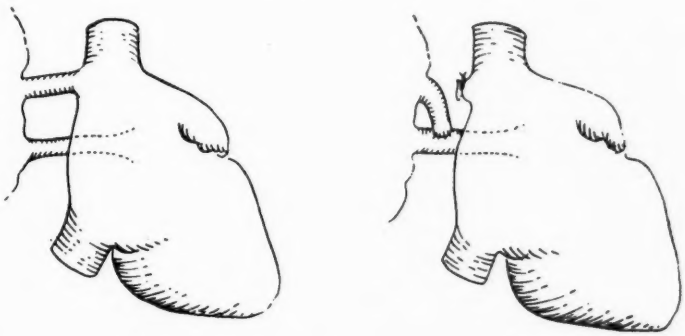


Fig. 8.—The creation of a septal defect for drainage of anomalous pulmonary veins by means of special intracardiac scissors.



A. *B.*

Fig. 9.—*A*, One right pulmonary vein anomalous (into superior vena cava), the other normal.

B, Surgical correction by implantation of end of divided abnormal vein into side of normal vein.

Should one or more of the right pulmonary veins enter directly into one of the venae cavae, one of the several logical modifications of these techniques will present itself. If one of the right pulmonary veins enters the left atrium,

the other (anomalous) one may be disinserted from the vena cava and anastomosed end-to-side to the normally draining vein (Fig. 9). Should one be anomalous into the right atrium while the other drains into the vena cava, the latter may be detached and anastomosed to the former. Then, atrioseptopexy may be carried out with application of the vein-bearing portion of the right atrial wall against the pre-existing or created septal defect.

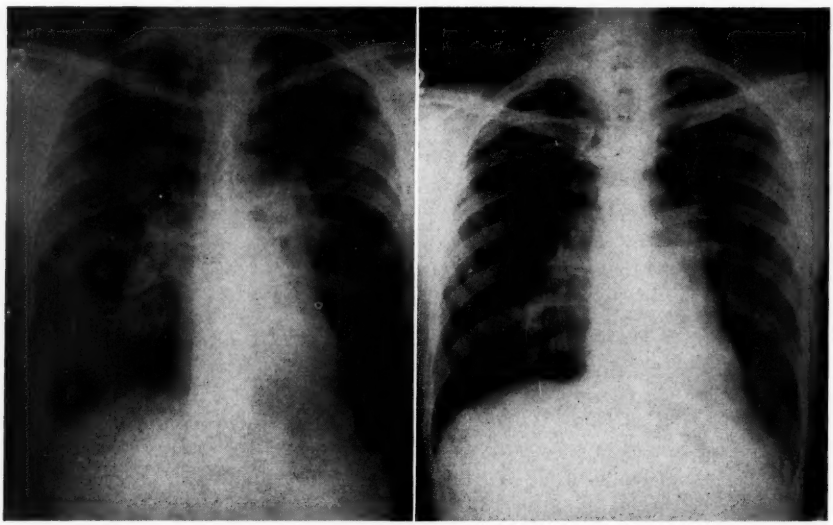
In case of total anomalous pulmonary venous drainage, the then necessarily present defect and the anomalous right pulmonary veins should be corrected at once. Retransposition of the anomalous left pulmonary veins may be performed at a later operation.

We feel that normal lung tissue should not be resected simply because of the existence of anomalous venous drainage unless there is no other feasible solution.

Coexistent Mitral Stenosis.—We now feel that a stenotic mitral valve may be more effectively treated by a right-sided approach[17, 18, 20, 21] than by the usual left-sided one, because the technically easier access to *both* commissures facilitates a more complete valve mobilization. From the right side, one is directly above the valve and in line with the left atrioventricular channel, whereas, when the mitral valve is attacked from the left side via the left auricular appendage, it can only be done with a finger bent back on itself or by the use of a valvulotome with an appropriate extreme curve or angulation.

ILLUSTRATIVE CASE REPORT

G. B. (No. 56-264439)), a 20-year-old white man, had been known to have a heart murmur since the age of 13. He had been almost free of symptoms up to the time of



A. *B.*

Fig. 10.—X-rays of G. B. *A*, Preoperative chest x-ray. *B*, Postoperative chest x-ray.

admission, except for some fatigability and some shortness of breath on heavy exertion. There was a harsh Grade 3 systolic murmur at the left third intercostal space near the sternal border. The pulmonary second sound was accentuated. The blood pressure was 120/80 mm. Hg. There was no cyanosis and no clubbing of the fingers or toes.

By x-ray, the heart was moderately enlarged (Fig. 10) with a prominent pulmonary artery and increased vascularity of the lungs. The electrocardiogram showed a normal sinus rhythm at a rate of 80, with right ventricular hypertrophy and strain. Cardiac catheterization revealed a left-to-right shunt at the atrial level of 6.8 L. per minute, with a normal pulmonary artery pressure.

Surgery was performed on Oct. 17, 1956. The right atrium was hugely dilated. The septal defect was a very large central one of the secundum type. There was a small (5 to 8 mm.) ridge of tissue about the periphery. The defect was approximately 5 to 6 cm. in diameter and oval. Its lower (caudal) margin lay about 5 cm. medial to the lateral atrial wall. It was successfully and easily closed by the above-described technique, the intracardiac index finger lifting the septal margin as the thumb depressed the lateral atrial wall to make contact with it. The time which elapsed from the insertion of the finger to closure of the defect was 22 minutes. The postoperative course was completely uneventful. At the present time, no murmurs are audible.

Since that time, 16 additional patients with ostium secundum defects have been treated easily and simply by this modified technique without operative mortality.

DISCUSSION

At the present time, three general plans of attack are available for closure of atrial septal defects. They are—the open, the semi-open ("well"), and the closed techniques. The open techniques entail the use of a pump-oxygenator, cross-circulation, or hypothermia. It is our opinion that these open surgical techniques are associated with greatly added risk and that their use is not justified for the closure of simple ostium secundum defects. The semi-open technique of Gross as elaborated by Kirklin seems to us to be unnecessarily complicated and time consuming for closure of a simple defect. Gross's recent adoption of the technique of atrioseptopexy would seem to imply a similar conclusion.

Ostium primum defects would seem to require an open technique for their closure. Defects with reversal of shunt represent an end stage of disease which may preclude correction by surgery. Associated lesions, such as mitral stenosis or anomalous drainage of the right pulmonary veins, may be treated definitively at the time of correction of a secundum type defect when the closed method of atrioseptopexy is employed.

SUMMARY

Simplicity, wide applicability, and safety to the patient distinguish the technique of atrioseptopexy as originally described. An open technique seems indicated for the correction of the less common and more difficult ostium primum type of lesion.

A modification of the technique of atrioseptopexy is suggested in which the intracardiac finger is introduced by way of a right-sided thoracic incision directly into the *left* atrium, so that it lies behind the interatrial septum, thereby considerably facilitating the steps of closure of the defect.

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VENTRICULAR FIBRILLATION IN HYPOTHERMIA

A Review of Factors Favoring Fibrillation in Hypothermia With and Without Cardiac Surgery

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IT IS generally agreed that ventricular fibrillation (VF) constitutes the most serious complication of profound hypothermia. It is still the main deterrent to the more extensive use of hypothermia for various surgical interventions despite the claim that it may be used to advantage in cardiac surgery.[1-4] In order to prevent this arrhythmia during hypothermia, particularly in cardiac surgery, it is necessary to know the factor(s) which induce it under such circumstances. Unfortunately, in spite of much work, there is still no general agreement about the exact mechanism of the onset of VF under normothermic conditions. The simplest working concept may be briefly outlined as follows: An ectopic focus or foci in the ventricles start discharging repetitively at a high and accelerating frequency (the high frequency is relative rather than absolute, being related to the refractory period of the muscle). If one of these impulses is discharged very soon after another it may be blocked on one side, provided it falls in the relative refractory period of the preceding impulse. However, the impulse traveling in other directions may proceed over the ventricular syncytium if the muscle has just recovered its excitability or is in a hyperexcitable state. Conditions are now favorable for re-entry and spread of excitation occurs in a very irregular and haphazard fashion depending upon the availability of excitable tissue. As a consequence, the ventricular contractions are fasciculated, producing the characteristic fibrillatory movements.

During hypothermia the physiology of practically every system in the body of the nonhibernating homeotherm is profoundly altered and it is the purpose of this review to analyze the role of these changes in favoring the onset of VF.

I. *Influence of Anesthetics.*—

Covino, Charleson, and D'Amato[5] noted that cardiac arrhythmias and VF occur less frequently in profoundly hypothermic dogs under thiopental or ether than under pentobarbital, whereas, in normothermic animals, arrhythmias are more frequent under Pentothal anesthesia. Riley and associates[6] similarly reported that there is a lower incidence of VF with thiopental anesthesia compared to pentobarbital.

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II. *Role of Cardiac Nerves.*—

The influence of extrinsic cardiac nerves on the VF of hypothermia is a moot question. Shumacker and colleagues[7] showed that bilateral sympathetic denervation of the heart or the use of a sympathetic ganglionic blocking agent (Arfonad) prevented fibrillation in hypothermic animals subjected to inflow occlusion and right ventriculotomy. On such grounds, Riberi,[8] Radigan[9] and their co-workers have used procaine infiltration of the junction of the right atrium with the superior vena cava and reported protection from VF during hypothermia and right ventriculotomy. Contrary to these observations, Covino and co-workers[5] found that adrenergic blockade with Dibenamine or SY-21 offered no protection against hypothermic VF in the absence of cardiac surgery.

Shumacker[7] noted that bilateral cervical vagotomy offered no protection. On the contrary, electrical stimulation of the undivided right vagus nerve below the level of the caudate ganglion reduced the incidence of VF. A similar result was noted by Montgomery, Prevedel, and Swan[10] who utilized vagal stimulation to prevent VF during catheterization of the coronary sinus in hypothermic animals.

From these studies one is led to conclude that increased sympathetic activity and perhaps decreased vagal tone on the heart tend to favor the onset of VF. Whether or not such a change in the activity of cardiac nerves prevails during hypothermia is uncertain, although some investigators[10] postulate that it does. This is thought to be a consequence of sino-aortic reflexes which may be activated from the fall of arterial pressure that occurs in hypothermia. The situation is actually much more complex than is implied by this hypothesis because there is some evidence that hypothermia affects the discharge of baroceptors as well as that of the medullary cardiac centers. Furthermore, the action of the neurohumoral agents (epinephrine and acetylcholine) released by the postganglionic nerve endings is increased in cold. Fuhrman and colleagues[11] showed that injected epinephrine causes an increase in the amplitude and duration of contraction of the denervated nictitating membrane at lower temperatures. This is explained by the action of cold in retarding the rate of enzymatic inactivation of epinephrine. Garb and Penna[12] showed that in isolated cat auricles, epinephrine produces a proportionately greater increase in rate and amplitude at 29° C. than at 37° C. Similarly, Jourdan and Marduel[13] have noted that vagal inhibition of heart lasts much longer in dogs at 30° C. than at 37° C., probably because enzymatic hydrolysis of acetylcholine is delayed by cold (acetylcholine esterase is less active at low temperatures). Some have erroneously interpreted this result to imply increased vagal tone during hypothermia.[14]

In contrast to the above results, the work of Reissmann and Kapoor[15] suggests that the extrinsic cardiac nerves play little if any role in precipitating VF in profoundly hypothermic dogs. They noted that the terminal hypothermic temperature at which VF supervenes is about the same in the denervated heart-lung preparation as in the intact dog. This comparison may be unjustified, however, on the grounds that conditions in the two preparations are not the same and that the interplay of different factors may have produced VF at the

same temperature. It would have been better to compare intact animals with others in which the hearts were previously denervated and the adrenals inactivated.

III. *Role of Blood Changes.* —

a. *Hormones:* Berne[16] has shown that the administration of epinephrine to the hypothermic heart precipitates VF. This is in line with the observation of Shumacker[7] that cardiac sympathectomy partially protects the heart from VF. Brown and Cotten[17] have noted that in hypothermic dogs there is an increase in the levels of circulating epinephrine and norepinephrine. Whether or not such increases play a role in precipitating VF in profound hypothermia remains problematic. From Reissmann's[15] studies, it appears that such factors are not involved. However, when cardiac inflow and outflow vessels are occluded in hypothermic animals or man, there may well be an appreciable accumulation of catechol amines in the inferior caval blood as a consequence of sino-aortic reflexes, and this may partly explain the high incidence of VF soon after the release of occlusion. On the basis of such a hypothesis, Cookson, Neptune, and Bailey[18] used a quick acting adrenergic blocking agent (Benodaine) which markedly reduced the incidence of VF following the release of venous occlusion. In contrast, Covino[5] observed that adrenergic blockade with Dibenamine or SY-21, given immediately before immersion, failed to afford protection against VF in severely hypothermic animals.

Recently, Watkins and colleagues[19] have shown that premedication with somatotrophin reduces the incidence of VF during cardiac surgery in hypothermic dogs as well as the VF produced by the ligation of a coronary artery in normothermic animals. The mechanism of action remains unknown. In this connection it would be of interest to know whether or not hypothermia alters the amount of circulating somatotrophin.

b. *pH changes:* It has been shown that hypothermia induces a respiratory as well as a metabolic acidosis in anesthetized animals breathing spontaneously. Brown and Miller[20] noted that normothermic dogs, made hypercapnic by breathing 30 to 40 per cent CO_2 for long periods, developed VF if suddenly placed on room air and hyperventilated. Swan and colleagues[21] presented data which suggested that VF in hypothermic dogs may be initiated by a sudden rise in blood pH from abnormally low levels. This was avoided to a certain extent by vigorous hyperventilation with oxygen to a state of alkalosis during the period of cooling and has been widely used by cardiac surgeons. Studies in the heart-lung preparation suggest that alkalemia does not play a role in precipitating or preventing VF in profound hypothermia.[22]

On the other hand, Moulder and co-workers[23] noted that a state of alkalosis is associated with considerable VF before surgery is done in hypothermic animals. These investigators recommend self-ventilation during cooling and minimal respiratory assistance after thoracotomy so as to maintain the blood pH near normal. Other workers[24] claim that ventilating the lungs with 2.5 to 11.5 per cent CO_2 in oxygen helps to prevent VF. Thus, it is clear that the problem is by no means settled.

Covino and Hegnauer[25] had emphasized the importance of acidosis in hypothermic VF and, in their preliminary studies, had suggested that acidosis favors VF by increasing the excitability of ventricular myocardium. However, in a more recent work the same investigators[26] showed that the earlier results were due to a technical error and that actually there were no changes in ventricular thresholds during hypothermia. Montgomery, Prevedel, and Swan[10] suggested that acidosis might possibly act by changing the potassium concentration in myocardial tissue. They noted that the hypothermic heart during respiratory acidosis gains K, whereas during respiratory alkalosis it maintains K balance.

c. *Plasma electrolytes:* Much interest is centered on the possible role of alterations in the concentration of plasma electrolytes on the onset of VF or cardiac asystole in hypothermia. Most investigators find no significant change in plasma sodium, chloride, phosphorus, and magnesium during hypothermia.

The cations of greatest interest are calcium and potassium because of their well-known effects on cardiac activity. In hypothermic dogs, Fleming[27] found no significant change in serum calcium whereas Smith[28] reported a 22 per cent increase. Elliott and Crismon[29] noted a slight increase in serum calcium in hypothermic rats that were shivering.

The studies on serum K are more inconsistent. Swan[21] and Osborn[30] found a decrease in K during hypothermia in dogs. Fleming[27] and Deterling and coworkers[31] reported no significant change whereas Smith[28] noted an increase of 45 per cent. Elliott and Crismon[29] found a marked rise of K in hypothermic rats undergoing shivering. This hyperpotassemia was attributed to hepatic glycogenolysis which is accompanied by the release of K. Whether the discrepant results in anesthetized dogs can be due to different degrees of shivering is difficult to know but appears unlikely.

In most of these studies, no correlation was made with terminal cardiac events. Hence, it is impossible to state whether or not these electrolyte changes are causally related to the onset of VF. Some investigators[32] have speculated that in hypothermia a rise of serum calcium/potassium ratio may be responsible for the onset of VF. However, the recent observation of Smith,[28] that the increase in potassium is proportionately greater than that of calcium, speaks against such a view. It may be significant to note that the hypothermic heart is more sensitive to K than the normothermic.[29]

d. *Shift of oxyhemoglobin dissociation curve:* Cooling the blood displaces the hemoglobin dissociation curve to the left, thus hindering the release of oxygen in systemic capillaries. On this basis, some workers[33, 34] postulated that hypothermia might induce hypoxia of all the tissues in the body including the myocardium. It was believed that both hypothermic VF and cardiac asystole were due to such myocardial hypoxia. However, Penrod[35] and Hegnauer and associates[36] showed that in the presence of adequate arterial saturation, coronary A-V oxygen difference remains unchanged at temperatures as low as 20° C. or 17° C. Studies by Badeer[22] demonstrated that in the heart-lung preparation increasing the amount of oxygen physically dissolved in the blood does not lower

the hypothermic temperature that induces VF when cardiac manipulation is avoided. Also, Berne[16] has shown that increasing the coronary flow, up to ninefold, in a hypothermic heart does not improve the performance of the heart as judged by pressure contours. These studies demonstrate beyond doubt that the leftward shift of the dissociation curve by cold does not induce hypoxia of the myocardium provided arterial saturation is normal.

e. *Arterial hypoxemia:* Beck and Leighninger[37] reported that in normothermic animals a progressive decrease in arterial saturation causes cardiac arrest by asystole and not by VF. It was explained that such a heart is "electrically stable" because hypoxemia affects the entire ventricular myocardium equally. Similarly, in fatal hemorrhage the entire heart is hypoxic and stops in asystole.

On such grounds one would expect that should hypoxemia prevail during hypothermia it would not contribute to the onset of VF.

IV. *Influence of Work Load of Heart.—*

Bigelow and co-workers[38] reported that VF in hypothermia was associated with a high central venous pressure and that it could be prevented by venesection. Covino and colleagues,[5] on the other hand, found that venesection did not prevent VF and concluded that cardiac overloading is not a contributing factor. This is in line with the finding of Reissmann[15] who noted no relationship between cardiac load and susceptibility to VF in the heart-lung preparation, except when the load was extreme and caused a relative deficiency of oxygen supply. Such a discrepancy between load and oxygen supply may arise on the sudden release of cardiac inflow occlusion under hypothermia because the heart is already hypoxic due to the occlusion. Therefore, release must be done in stages to avoid overloading.

V. *Direct Effect of Lowered Temperature on Heart Muscle.—*

a. *Excitability:* As already pointed out, the recent work of Hegnauer and Covino[26] shows that there is no change in the intensity of threshold stimuli applied to the hypothermic ventricular myocardium at different periods of the cardiac cycle even in the presence of acidosis. Hence, it is misleading to speak of an increased "irritability" of the ventricles during hypothermia.

Studies by Coraboeuf and Weidmann[39] on single Purkinje fibers, utilizing the intracellular recording technique, showed that the magnitude of resting potential and of the spike potential is unchanged between 40° C. and 25° C., but the duration of all the phases is prolonged with fall of temperature. This result may be interpreted to indicate a slowing of the speed of migration of ions during reversed polarization (depolarization) and repolarization of Purkinje tissue, but the magnitude of ionic migration (number of ions) seems to be unchanged. Similar results were obtained on single fibers of frog ventricle and cat auricle. These findings at the cellular level agree with the latest report of Hegnauer[26] that there are no changes in the threshold of excitability of dog ventricle during hypothermia, assuming that polarization phenomena represent excitability.

We may conclude, therefore, that changes in myocardial excitability are not involved in hypothermic VF.

b. *Speed of conduction, contraction, and relaxation:* All these events are slowed during hypothermia. Slowing of conduction is indicated by the well-known prolongation of the P-R interval, widening of QRS, elevation of S-T segment and changes in the contour of P and T waves.[40]

Ventricular contraction and relaxation phases are markedly prolonged during hypothermia.[41] These changes are accompanied by lengthening of both the absolute and relative refractory periods of the ventricle.[42] Such findings agree with the observation in single fibers that all phases of electrical activity are prolonged with fall of temperature.[39]

c. *Temperature gradients:* Hegnauer[43] pointed out that during hypothermia and rewarming one would expect significant temperature variations in the ventricular myocardium and that such gradients may be responsible for ectopic activity in the ventricles. Pinkston and associates[42] have recently demonstrated the existence of such gradients by thermocouples placed at various parts of the heart. These gradients could readily produce differences in the relative refractory period in different parts of the ventricular myocardium and thus play an important role in precipitating VF by blocking an ectopic impulse in some areas and allowing it to travel in others.

d. *Ventricular ectopic activity:* Experimental evidence indicates that at temperatures below 25° C. there is a tendency for the development of ectopic foci in the ventricles. Since the pathophysiology of ectopic discharges is still not well understood it is difficult to state the mechanism of ventricular ectopic activity in hypothermia. According to Di Palma,[14] acute failure of sinus activity may be a cause of ventricular rhythms. These ectopic discharges, specially when accelerating, may be blocked unilaterally as a consequence of differences in the refractory period and thus initiate re-entry and VF. It is likely that such discharges come during the so-called "vulnerable period" of ventricular activity (end of systole) in order to cause fibrillation. Many workers suspect that changes in pH and/or K of ventricular myocardium are somehow involved in ectopic activity and the onset of VF.

e. *Myocardial electrolytes:* Montgomery and co-workers[10] reported that in hypothermic acidotic animals which terminate by VF, the myocardium gains K prior to the arrhythmia, whereas in alkalotic animals there is no change. Later studies by Covino and Hegnauer[44] gave different results: In hypothermic acidotic dogs which terminated by VF, there was a loss of K and H ions from cardiac muscle and a gain of calcium. However, in those animals that did not end by VF, the myocardium neither gained nor lost these ions. The authors explain the discrepant results of Montgomery and co-workers[10] on the basis that these workers used vagal stimulation or acetylcholine or Prostigmin in their experiments and that these chemicals are known to alter the K balance of the heart. Recently, Smith,[28] in agreement with Covino and Hegnauer,[44] also noted a loss of K from heart muscle just prior to VF in many of his experiments. Currently much interest is centered on the role of K but more research is needed to assign its exact role.

Covino and Hegnauer[44] reported that there was no gain or loss of myocardial sodium, chloride, and magnesium in hypothermic fibrillators or nonfibrillators.

VI. *Mechanical Stimuli.*—

It is well known that manipulating, clamping, or cutting the heart, as well as the presence of intraventricular catheters act as mechanical stimuli even under normothermic conditions. In normothermia such stimuli rarely induce VF. In the cold state, on the contrary, such stimuli are potent factors precipitating VF.[15, 36] The difference probably lies in the slowed conduction and variations in the refractory period of different parts of the hypothermic myocardium.

VII. *Coronary Blood Flow.*—

All investigators agree that in hypothermia there is a reduction in coronary flow.[16,45-47] Although Smith[28] claims that the decline in coronary flow leads to hypoxia of the heart and is a factor in the onset of VF, the majority of workers[16, 22, 35, 36, 47, 48] agree that there is no evidence of myocardial hypoxia in hypothermia. The oxygen demand of the heart is greatly reduced by the low myocardial temperature, the reduced cardiac output and arterial pressure and the bradycardia. All these cut down the demand for oxygen so much that the curtailed coronary flow presumably remains adequate for the requirements of the myocardium. Hence, VF during profound hypothermia, in the absence of cardiac manipulation and inflow occlusion, is not due to myocardial hypoxia.

In cardiac surgery with inflow occlusion under moderate hypothermia, the situation is somewhat different. The ventricles are now subjected to a diffuse ischemia and the question arises whether or not such ischemic hypoxia contributes to the onset of VF which usually develops some time after occlusion. If Beck's view (see *Arterial Hypoxemia*) is correct, such diffuse ischemia should not play a role in VF. However, Edwards,[49] Lewis,[50] and their associates showed recently that perfusion of the coronaries with oxygenated blood during the period of occlusion markedly reduces the incidence of VF. These reports suggest, contrary to Beck's hypothesis, that diffuse hypoxia of the myocardium may be a factor leading to VF, at least in the hypothermic heart.

CONCLUSION

Ventricular fibrillation in hypothermia with and without cardiac surgery is not due to the operation of any one factor. The tendency for the development of accelerating discharges from ectopic centers in the ventricles coupled with prolongation and variation in the relative refractory period produced by the lowered temperature seem to be the most important factors initiating VF. Conditions that favor ventricular ectopic discharges, such as, changes in blood pH, disturbed myocardial Ca-K balance, mechanical stimuli, increased activity of cardiac sympathetics, increased amounts of circulating catechol amines, interference with coronary arterial flow, anesthetics and drugs, etc.,

favor the onset of VF during hypothermia. It appears that prolongation of the refractory period due to cold per se and differences in the refractory period due to temperature gradients pave the way for the onset of VF.

Prevention by physiologic and pharmacologic means should aim at reducing or eliminating these factors as much as possible.

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CARCINOMA OF THE LUNG TREATED BY LOBECTOMY: THE PROBLEM OF LOCAL RECURRENCE

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AS THE pendulum swings from the more radical extirpations of carcinoma of the lung to lesser resections, the problem of local recurrence assumes a more prominent role. This recurrence, be it in the bronchial stump or in the hilar lymph nodes, is a poor reflection on the operative procedure, especially if it was an elective lobectomy or bilobectomy. Pneumonectomy, bilobectomy, and lobectomy in selected cases of carcinoma of the lung have yielded fairly good results[1-3] and, at present, represents our only effective weapon against this disease. Therefore, it is felt that the underlying pathology and the pulmonary functional status of the patient should determine the extent of resection rather than enthusiasm for a particular operative procedure or the unsuppressed desire to preserve all normal lung tissue.

Recently, Habein, McDonald, and Clagett[4] reviewed 18 cases of recurrent carcinomas of the bronchial stump in a series of six hundred and thirty-one extirpations and resections for carcinoma of the lung (an incidence of 2.9 per cent). In this group there were no known recurrences in the lobectomy group and only two in the bilobectomy group. In our series of twenty-one lobectomies and bilobectomies for carcinoma of the lung, performed prior to February, 1955, there are two known recurrences (an incidence of 9.5 per cent) and 2 suspected recurrences in patients who died at home. Because of the difficulty in following all patients personally, who have had resections for carcinoma of the lung, we have considered the presence of persistent cough, hemoptysis, and inanition as evidence of recurrence until proved otherwise.

The two proved recurrences in our series of twenty-one resections (sixteen of which were for squamous-cell carcinomas) and an additional case, a patient whose lung had been resected in another hospital and who had been followed on this service until death, were all squamous-cell carcinomas. Also, the 18 cases of Habein, McDonald, and Clagett,[4] previously referred to, were all squamous-cell carcinomas.

CASE REPORTS

CASE 1. The patient, a 58-year-old white man, was admitted to the VA Hospital, McKinney, Texas, in December of 1954, for the sixth time during the past eight years for a chronic inflammation of the upper eyelid and an active duodenal ulcer. Routine x-ray on this admission disclosed an infiltrate about 5 cm. in diameter in the right lower lobe

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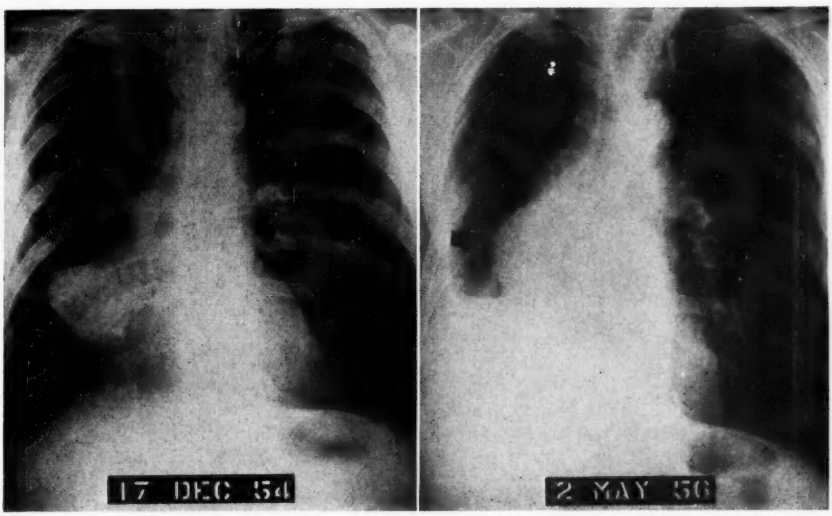
(Fig. 1, *A*) which was not present on a film taken in May of 1952. In reviewing his history, it was found that he was a heavy cigarette smoker, and had had a chronic cough for the past twenty years. During the past six months his cough had become productive and hemoptysis had occurred on several occasions.

Physical examination revealed an expiratory wheeze in the right lung field, anteriorly. He had deformities of the right leg and foot which were residuals of an anterior poliomyelitis that he had had as a child.

Clinical laboratory findings were all within normal limits. Pulmonary function studies including a total vital capacity and maximum breathing capacity were 66 per cent of the predicted normals.

Bronchoscopy disclosed a granular tumor in the basilar segmental bronchi of the right lower lobe that was reported by the pathologist to be a squamous-cell carcinoma. In January, 1955, a right middle and lower lobectomy were performed. Epithelial metaplasia was found on the cut end of the bronchus; however, because of emphysema on the left side and the patient's shortness of breath, it was decided not to remove the remaining lobe on the right.



A. *B.*

Fig. 1.—Case 1. *A*, Chest roentgenogram showing the carcinoma in the right lower lobe. *B*, Postoperative recurrence sixteen months after a right middle and lower lobectomy.

He remained well other than shortness of breath and ulcer symptoms until May of 1956, at which time he was readmitted with hemoptysis of three days' duration. Chest x-ray at this time revealed a large recurrent tumor in the right lower lung field (Fig. 1, *B*). Bronchoscopy also showed tumor extending up to the carina on the right. X-ray treatment was started and he was finally discharged in July, 1956, after receiving a tumor dose of 2,200 r. At present he is living a quiescent life in a government domicile.

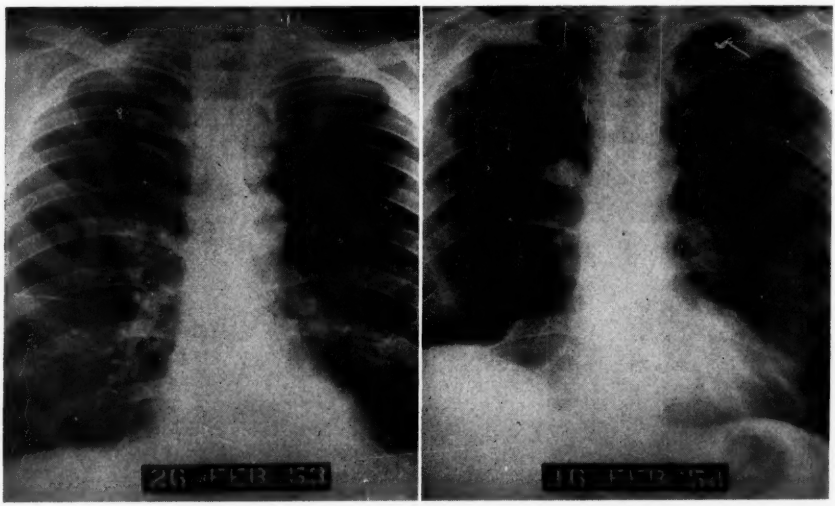
Case 2. The patient was a 41-year-old white man admitted to VA Hospital, McKinney, Texas, in February, 1953, with a history of progressive shortness of breath since August, 1952. He smoked cigarettes heavily and had had a chronic cough for the previous twenty-five years.

Physical examination disclosed only distant breath sounds over the left apex anteriorly and expiratory râles over the entire right hemithorax.

Laboratory studies were all within normal limits. Roentgenograms of the chest revealed several thin walled cysts in the left upper lung field and a nodular lesion in the right hilum (Fig. 2, *A*). Pulmonary functions preoperatively showed the following: maximum breathing capacity, 111 L. per minute, and a total vital capacity of 1.1 L. in ½ second, 2.0 L. in one second, and 2.8 L. in 1½ seconds. There was little change after the first operation.

In March, 1953, two large blebs were excised from the apical segment of the left upper lobe and a smaller one from the lingula of the left lower lobe, following which poudrage was carried out over the left upper lobe. The patient tolerated this procedure well and in May, 1953, a right upper lobectomy was performed for a deep-seated squamous-cell carcinoma. Pneumonectomy was not performed because of the presence of bilateral emphysema and because it was felt that lobectomy had removed the tumor completely.

Pathologic sections of the cut end of the bronchus and adjacent lymph nodes revealed no evidence of tumor.



A. *B.*

Fig. 2.—Case 2. *A*, Chest roentgenogram demonstrating the carcinoma in the right upper lobe. *B*, Postoperative recurrence one year after a right upper lobectomy.

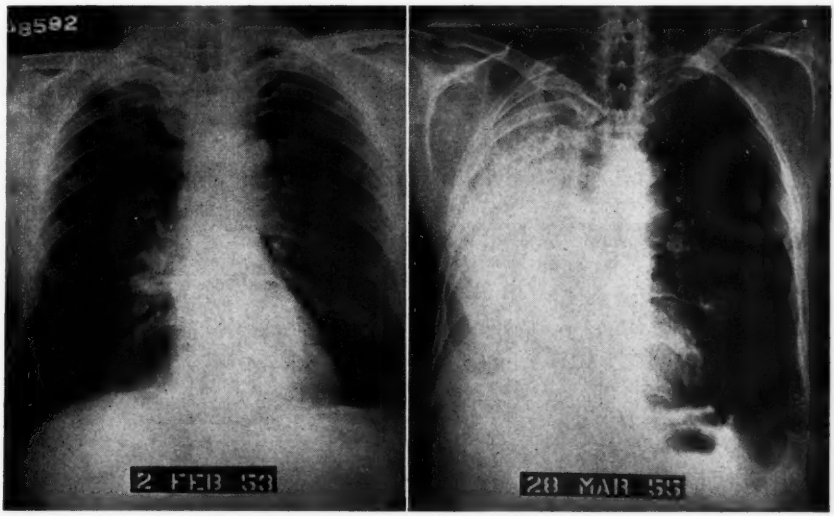
The patient did well until February, 1954, when a follow-up chest roentgenogram showed a recurrent tumor in the right hilum (Fig. 2, *B*). Bronchial secretions were positive for tumor cells. X-ray therapy was given at this time, but despite this the mass grew larger. Several other nodules developed in the right lower lobe, and the patient died with cerebral metastasis on Sept. 30, 1955. Permission to perform an autopsy was refused.

CASE 3. The patient was a 58-year-old white male salesman admitted to VA Hospital, Dallas, in October, 1954, with the complaint of a firm, tender mass in the right supraclavicular fossa. This mass had been present for three months prior to admission and was growing larger. In February of 1953, this patient had had a routine roentgenogram of the chest taken at the VA Regional Office (Fig. 3, *A*) which showed an infiltrate in the right lower lobe. He returned to a private physician who also studied him and he was told that he had a tumor in the right lung. On March 2, 1953, a right middle and lower lobectomy was performed in another hospital and he had an uneventful convalescence from this procedure until the right supraclavicular tumor manifested itself. His past history and systemic review were noncontributory.

Physical examination, on admission, disclosed several scars over his face where skin cancers had been removed, and he wore an artificial limb on the left lower leg which had been amputated, in 1922, for a chronic osteomyelitis. A firm mass about 4 cm. in diameter was present in the right supraclavicular fossa which was attached to the deep structures below it. He also had a well-healed posterior lateral thoracotomy scar on the right and some limited expansion of the right hemithorax. Breath sounds on the right were somewhat limited in comparison to those on the left.

Laboratory studies revealed a slight anemia. Roentgenograms of the chest revealed an increased density in the anterior segment of the left upper lobe with several other small infiltrates below it and the usual postoperative changes in the right lung.

Biopsy of the supraclavicular mass revealed a metastatic squamous-cell carcinoma which resembled the primary tumor removed from the lung. Both were poorly differentiated. X-ray therapy was administered to the right supraclavicular tumor which responded fairly well. He was discharged but was readmitted for the last time with some condylomata



A. *B.*

Fig. 3.—Case 3. *A*, Chest x-ray showing the carcinoma in the right lower lobe. *B*. Postoperative recurrence with atelectasis of the right upper lobe twenty-five months after a right middle and lower lobectomy.

acuminata and another squamous-cell carcinoma of the right wrist. Both of these tumors were removed without incident; however, during his hospitalization he developed a fever, and a severe cough, followed by a rapid downhill course. Chest studies disclosed a pneumonia in the right lung field with a questionable effusion. This later developed into a complete atelectasis of the remaining right upper lobe (Fig. 3, *B*). On April 4, 1955, he had two clonic convulsions and died shortly thereafter. Autopsy revealed a recurrent carcinoma of the bronchial stump on the right which had occluded the right upper lobe bronchus. There were also metastatic carcinoma sites in the left lung, right adrenal, and mediastinal lymph nodes.

DISCUSSION

The grave potential of a squamous-cell carcinoma of the lung is clearly illustrated in these 3 cases, and it is now our feeling that most squamous-cell carcinomas should be treated by pneumonectomy. Lobectomy and bilobectomy

should be reserved for some peripherally placed adenocarcinomas, large-cell undifferentiated carcinomas, and bronchiolar carcinomas, if the hilar lymph nodes are negative for carcinoma on frozen section.

The so-called "safe margin" of 1.5 cm. of tumor-free bronchus proximal to a squamous-cell carcinoma, as described by Griess, McDonald, and Clagett,[5] has not been reliable in our experience or in that of others.[4] Frozen section of the cut end of the bronchus seems to be the most dependable method of ascertaining the presence of tumor cells or metaplasia. Epithelial metaplasia has been found to be an ominous sign and probably all suspected cases of carcinoma of the lung should have multiple biopsies of the lobar bronchus and paracarinal area, as suggested by Rabin, Selikoff and Kramer,[6] to determine their operability.

SUMMARY AND CONCLUSIONS

1. Two proved cases and two probable cases of recurrent squamous-cell carcinoma of the bronchial stump occurred in a series of 21 lobectomies for carcinoma of the lung.

2. The exact incidence of this condition is probably underestimated because of the difficulty in following all patients in person. The symptoms of a persistent cough, hemoptysis, and inanition are considered evidence of bronchial stump recurrence until proved otherwise.

3. The prognosis of a local recurrence is poor. Radiation therapy has been of little or no help and further surgery was considered meddlesome.

4. It is felt that the underlying pathology and pulmonary functional status of the patient should determine the extent of resection rather than enthusiasm for a particular operative procedure or the unsuppressed desire to preserve all normal lung tissue.

5. For the most part, squamous-cell carcinomas should be treated by pneumonectomy.

6. Lobectomy and bilobectomy should be reserved for some peripherally placed adenocarcinomas and large-cell undifferentiated carcinomas if the hilar lymph nodes are negative for carcinoma on frozen section.

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